EXPERIMENTAL INVESTIGATION INTO THE FATIGUE RESPONSE AND ULTIMATE STRENGTH PERFORMANCE OF CONCRETE FILLED GRID BRIDGE DECKS

by

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ABSTRACT

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EXPERIMENTAL INVESTIGATION INTO THE FATIGUE RESPONSE AND ULTIMATE STRENGTH PERFORMANCE OF CONCRETE FILLED GRID BRIDGE DECKS

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Most bridges located in major cities experience large traffic volumes, which require bridge decks to be extremely durable under this constant loading. Concrete filled steel grid bridge decks have exhibited extended service lives under severe urban traffic conditions, and in some instances, have been in use for more than 60 years. Concrete filled steel grid decking can be a viable option for both decking and re-decking operations since it can be installed quickly, and because it can be equipped with stay-in-place form pans.

The current PennDOT BD-604 design standard appears to be conservative in its specification of allowable span lengths. The present research will investigate the use of concrete filled steel grid deck on greater span lengths. The BD-604 is based on the performance of older grid deck installations, and does not take advantage of modern materials, or more advanced analysis and design techniques.

An experimental evaluation of the fatigue and ultimate strength performance of a series of full-depth, overfilled, two span continuous grid deck panels on a simulated 10' stringer spacing is carried out. The testing was conducted at the University of Pittsburgh Main Campus in the Watkins-Haggart Structural Testing Laboratory in Benedum Hall. Based on the results from this testing it appears that the span lengths in the BD-604 may be increased by a factor of 1.67.

DESCRIPTORS

Concrete Filled Steel Grid Deck

Bridge Deck

Fatigue Testing

Ultimate Strength Testing

FOREWORD

The completion of this thesis is directly related to the efforts, sometimes extraordinary, of an extremely dedicated faculty advisor, and supporting committee, without whom this work would not have been a reality. Also, without the assistance of many talented students, who aided in everything from concrete pours to placing strain gauges, this thesis would never have been completed. This thesis displays the laboratory conclusions that will hopefully make concrete filled bridge grid decks a more viable option for both bridge construction and rehabilitation.

While here at the University of Pittsburgh, there is a large list of people to thank for helping me become a better person. I would like to thank the many companies who donated materials as well as sound technical knowledge. Also, I would like to thank my committee members for their help and support with the development of this work. In addition, the faculty and staff of the Department of Civil and Environmental Engineering for their overwhelming support of my education throughout my years here at the University of Pittsburgh.

Last but certainly not least, I extend my deepest gratitude to Dr. C.J. Earls, for granting me the privilege to attend graduate school and study under him. Dr. Earls has been very essential in my development as an engineer, as well as a person. I am forever grateful for the experience, the technical knowledge, as well as the friendship that I have gained while at the University of Pittsburgh

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1.0 INTRODUCTION

1.1 Introduction to Grid Decking

Most bridges in major cities experience large traffic volumes, which require the bridge deck to be extremely durable under this constant loading. Grid decks have shown an extended service life under severe urban traffic conditions, in some instances these decks have been in use for close to 60 years. Grid decks have been used on many bridges throughout the country, including some here in the Pittsburgh area. Some examples of these bridges that have utilized grid decking are, South 10th Street Bridge, Pittsburgh (1934), Boston Bridge, Boston, Pa (1936), Jerome Street Bridge, McKeesport (1938), Homestead Hi-Level Bridge, Homestead (1938), all of which have their original grid reinforced concrete decks still in use (BGFMA, 1999). The Jerome Street Bridge, the Elizabeth Bridge (1950) and the Walt Whitman Bridge, Philadelphia (1956), have all had their conventional reinforced concrete decks replaced on the approach spans, while the grid reinforced deck on the main spans, which were subjected to the same traffic and climate conditions, has only required resurfacing (BGFMA, 1999).

As a precursor to the remainder of the introduction, some terminology will be discussed. Concrete filled grid decking is made up of several structural elements: These elements include main bars; upper cross bars; lower cross bars; supplemental bars; form pans; and concrete fill. These individual structural elements will be discussed in detail.

The main bar, also be referred to as a bearing bar, is a rolled section, that closely resembles a small I-shaped beam. The main bars can be orientated in two different ways:

transverse, which is perpendicular to traffic; or longitudinal, which is parallel to traffic. When the main bars are placed transversely, the bars span between the stringers. Conversely, when the main bars are placed parallel, they are orientated parallel with the traffic flow. Frequently the grid deck's main bars are continuous over several supports. The main bars are pierced by a series of punch-outs along the length made by using specially manufactured dies in a punching machine. These punch-outs are used to accommodate the upper cross bars.

The cross bars complete the grid geometry by being placed perpendicular to the main bars. The upper cross bars are inserted through the punched hole in the web of the main bar and are subsequently held in place by puddle welds at the intersection with the main bars. These bars are made from flat rectangular stock, and are orientated with their weak axis vertical. Notches in the top edge of the upper cross bar are made so that the top flange of the main bar can sit flush with the top of the upper cross bar. In addition, the upper cross bars may also notched to accept optional supplemental bars.
The supplemental bars are installed between the main bars and orientated so that their longitudinal axis is parallel with the main bars' longitudinal axis. The supplemental bars add more stiffness in the main bar direction. The bars are usually rectangular or round in cross section. The rectangular bars are notched in order to sit flush with the main bars. The round bars can be installed by drilling a hole in the upper cross-bars, and inserting the round bar through these holes.

The lower cross bars are orientated perpendicular to the main bars and are usually made from a round concrete reinforcing bar. A hole must be punched in the main bar just above the bottom flange to accommodate the lower cross bar, which is then simply inserted through the holes.

Light gauge, stay-in place, metal form pans are one of the factors that make filled grid deck an attractive option for use in bridge construction. The form pans are made of 20-gauge sheet steel and are placed between, and supported by, the bottom flanges of the main bars. The pans are attached by tack welding them to the main bars about every eight inches. The use of form pans on the grid deck makes it a competitive option for bridge decking, since formwork will not have to be constructed on the site, and the formwork will not have to be removed once the concrete has cured.

Concrete fill increases the stiffness of the deck, and it also provides lateral support for both the main bars and the cross bars. The concrete fill can extend over the full depth of the main bar, or only half the depth of the main bar. The concrete can be made flush with the top of the grid, or it can overlay the top of the grid (termed “overfill”). The overfill of the grid above the top of the main bars is usually between 1 ½”and 1 ¾”. Both normal weight and lightweight concrete can be used for the concrete fill. The maximum aggregate size is 3/8 inch, due to the close spacing of the elements in the grid work

The grid decking can be installed very quickly when manufactured in prefabricated sections. The grid decking is then attached to the girders or floor beams of the bridge by using shear studs, welding, or by using threaded bolts. At the location of the grid deck and the framing member a haunch is typically formed in order to ensure composite behavior of the grid deck and the support member. The haunch is created by using shear studs on the support member (making sure the shear studs do not interfere with the grid) and by omitting the concrete form pan over the support member so as to allow the shear studs to pierce the plane of the grid deck. In most cases the bottom of the grid deck will actually be at a higher elevation than at the top of the supporting member. Haunch forms can be made by using the concrete form pans at an angle, or by welding a steel plate, or an angle section to the support member in order to create an area for the concrete to be placed. Appendix C, Figure C-13 shows the different ways of forming a haunch, and the different methods of attaching the grid deck to the supporting member.

There are a variety of ways in which splicing can be achieved. The main bar splice can be accomplished in one of two ways: weld a plate (the same depth of the main bars) to the main bars of one panel, and then field weld the main bars of the second panel to this plate; or weld a plate to the main bars of each panel section and then bolt these plates together. The welding in the second option would be done in the fabrication shop. Appendix C, Figure C-13 shows the two different splicing options.

There are two viable options for splicing upper and lower cross-bars. One method is a weldless option. Looking in plan view, a small gap is allowed between the upper and lower cross bars. Rebar is then field installed every 8” along the splice length. The rebar is positioned in the punch-outs next to the upper cross bars. The bottom rebar is placed between the bottom cross bars at a location of ½ the distance between two lower cross bars, thus staggering the top and bottom rebar. The second option for splicing the cross bars is to overlap the upper cross-bars by 1”, and the lower cross bars by 2”. The bars are then field welded together. Appendix C, Figure C-13, shows the details of the different splicing of both the upper and lower cross bars.

Also, it should be noted that expansion and relief joints can be installed on the grid deck instead of the upper and lower cross bar splice. A ½" plate is shop welded to the ends of the cross bars and some kind of seal can be installed between the two panels. A detailed drawing of the expansion and relief joints is located in Appendix C, Figure C-13.

1.2 Literature Review of Earlier Research

1.2.1 Fatigue Testing

Mangelsdorf (1996) performed fatigue tests on five "full size" specimens with five different grid geometries. The specimens were subjected to cyclical loadings and the tests "were terminated when at least two elements of each deck had cracked" (Mangelsdorf, 1996). Mangelsdorf also tested 14 filled specimens consisting of only two main bars. These specimens were tested under a cyclical load of constant amplitude strain until "either the specimens survived 10 or more million cycles or at least one main bar cracked" (Mangelsdorf, 1996). As a result of this research work, Mangelsdorf categorizes filled grid as Category "C" in the AASHTO's LRFD specifications. However, as noted later in this review, Mertz and Jurkovic (1996) believe that filled grid decks should be classified under a more favorable LRFD fatigue category.

In order to perform the fatigue testing, Manglesdorf used an Ametek model SC-20 pulsator operating at 1.5 and 2 cycles per second. "The actuators were always single acting with the peak load typically about 5% higher than the load range in order to maintain physical contact between all elements during the cycle" (Mangelsdorf, 1996).

After testing, the initiation site of main bar fracture was investigated by removing concrete from the grid around the loading points. “Of the 30 positive moment cracks, 29 were found to have started at the non-structural tack welds connecting the form pan to the top of the bottom flange” (Mangelsdorf, 1996). The remaining crack may have occurred at a round bar punch-out in the web at the bottom flange of the main bar. Two negative moment cracks were found on the FAT 2 specimen (3-inch Tee section) at the crossbar punch out on the other side of the crossbar from the weld.

Mangelsdorf concludes that the primary stress raisers in positive bending are the form pan tack welds. Mangelsdorf, however, points out that failure has not been observed in these locations in field installations. This is evidence that the stress level in the field has never been great enough to generate a fracture. Mangelsdorf warns that if deck spans are increased beyond those used in current practice, the tack welds will eventually govern.

Based on the results from Mangelsdorf’s fatigue testing, overfilled decks are “deemed equivalent to flush filled ones in the negative moment regions of continuous spans” (Mangelsdorf, 1996). The added concrete from the overfill does not raise the neutral axis and “thereby lower the stress at the top of the weld” (Mangelsdorf, 1996). Mangelsdorf also states that the influence of hole shape, concrete encasement, and overfill, on the effective fatigue category of the details, is hidden by variations in the data

Mertz and Jurkovic (1996) explain why the laboratory fatigue performance of Mangelsdorf’s (1996) steel grid-reinforced concrete decks does not agree with actual fatigue resistance of field installations: Mangelsdorf tested at elevated stress levels, greater than those experienced in the field, to accelerate his fatigue-testing program. "Inherent in the assumption that a higher stress range, causing cracking at a lower number of cycles, can be used to quantify fatigue resistance at more realistic stress-range levels is the further assumption that the elevated stress range will not alter the mode of failure" (Mertz & Jurkovic, 1996). collected (i.e. experimental error).

Fatigue test results of Mangelsdorf (1996) showed debonding of the concrete from the steel grid before fatigue cracking (Mertz & Jurkovic, 1996). Concrete debonding has not been observed in in-service decks and removal of concrete from decks taken out of service is nearly impossible (Mertz & Jurkovic, 1996). "Apparently, the levels of stress experienced by in-service decks is [sic] below the threshold which causes debonding of the concrete" (Mertz & Jurkovic, 1996). The fatigue test results, conducted by Mangelsdorf, are not correct since the artificially high stress ranges result in a "premature, and unrealistic failure, debonding of the concrete from the steel grid, prior to fatigue cracking" (Mertz & Jurkovic, 1996). Thus, the actual fatigue resistance of steel grid-reinforced concrete decks could be greater than the suggested Category "C". In order to perform accelerated fatigue testing, the stress levels must be below the concrete debonding limitation in order to determine the finite-life fatigue resistance of the specimens.

1.2.2 Ultimate Strength

Mangelsdorf performed ultimate strength tests using two single-point load specimens with all edges simply supported and seven line load specimens with simple spans in the strong or weak directions. The point load cases were simply supported over 7'-6" spans at the ends of the strong direction while the corners of the decks were not held down. The STAT 1 specimen was stiffened by a continuous weld along the edge beams to the top and bottom flanges of W4x13's. In the STAT 4 specimen, posts provided support to the other two edges. An eight-inch diameter circular steel pad, centrally located, provided the loading for both cases. Mangelsdorf measured deflections at the center and, for STAT 1, along the stiffened edge.

Mangelsdorf states that supplementary bars parallel to the main bars are assumed to contribute to the plastic moment resistance with 100% effectiveness. "This assumption is justified by a comparison, for example, of the compression strains in the top of a main bar and an adjacent supplementary bar in STAT 8" (Mangelsdorf, 1996). However, during early loading stages, evidence suggests only 50% effectiveness; this may be explained by the result of early debonding. This loss of effectiveness due to debonding "may have been recovered by the closing of gaps and the consequent effective shear transfer through the concrete (Mangelsdorf, 1996).

In the main bar direction, ultimate positive moment was calculated from a "semirational equation based on the line load tests results" (Mangelsdorf, 1996). "The assumption was made that the plastic moment of an open section is enhanced by the contribution of the concrete in proportion to the ratio of the area of concrete, multiplied by f'c, to the area of steel, multiplied by Fy" (Mangelsdorf, 1996). Mangelsdorf provides the resulting equation for full depth overfilled sections as

$$M_{ux} := \frac{Zx \cdot Fy}{b} \cdot \left(1 + \frac{0.2 \cdot fc \cdot b \cdot d^3}{As \cdot Fy \cdot h^2}\right)$$

where M_{ux} is the unit moment resistance, b is the width of the section considered, 0.2 is an empirically determined constant, d is the depth of concrete fill and h is the depth of the steel section. "For half depth, flush filled decks the factor d_2/h_2 can be taken as unity by assuming that the missing concrete on the bottom would not be effective anyway" (Mangelsdorf, 1996). For half depth, overfilled sections it would be reasonable and most likely conservative to take d as the overall depth of the deck. Overfill can be ignored in the negative moment regions for full depth sections (Mangelsdorf, 1996).

Through Mangelsdorf's (1996) ultimate strength tests, the strength resistance of filled grids "has been found to greatly exceed any reasonable vehicle loading." This has been verified by using "experimentally determined ultimate moments applied to yield line theory" (Mangelsdorf, 1996). Ultimate strength or even allowable stress in working stress design, therefore, need not be considered. (Mangelsdorf, 1996).

1.3 Objective of Research

The Pennsylvania Department of Transportation (PennDOT) has approved the use of concrete filled grid deck for bridge designs, as specified in the PennDOT Interim

Standard BD-604. Currently the BD-604 appears to be overly conservative in its span limitations for various grid deck geometries; many other states have been using concrete filled grid decks on larger stringer spacing than what the BD-604 currently allows. The BD-604 is based on the service record for older grid deck installations, and does not take advantage of modern materials and an understanding of how a grid deck actually behaves.

The objective of the present research program is to perform an experimental evaluation of the fatigue and ultimate strength performance of a series of full-depth, overfilled two-span-continuous grid deck panels used at a simulated 10’ stringer spacing.

1.4 Thesis Overview

This thesis is organized into five sections, which describe the research conducted and the results obtained. The first section is the introduction. Section 2.0 presents the details of the experimental testing that was performed as part of this research. Section 3.0 is a discussion of the results. Section 4.0 is used to present the conclusions that have been drawn from the present research and recommendations for future studies. The appendices provide the experimental results, pictures, drawings, and plans of the experimental specimens, as well the location of the instrumentation of the test specimens.

2.0 EXPERIMENTAL STUDIES

2.1 Description of Specimens

The grid deck specimens chosen for both the fatigue the ultimate strength testing are identical in overall geometry, and element size (See Appendix C, Figures C-1 through C-3, for drawings and details of the grid deck specimens). A total of four grid deck specimens will be evaluated. The overall dimensions of specimens are 20'long, 6' wide, and 7" deep (the concrete was placed through the full depth with the 1 ¾"concrete over fill). The grid decks were constructed at a local fabrication shop. The fabrication included placing of the main bars, upper cross bars, supplemental bars, and concrete form pans. All of the welding was also performed at the fabrication shop. Once the fabrication was complete, the decks were delivered to the University of Pittsburgh where additional fabrication took place.

The grid decks consisted of main bars with an overall depth was 5-3/16". Upper cross bars occur perpendicular to the main bars every 4" on center. The upper cross bars are 2"x ¼" and are rectangular in cross section. Supplemental bars perpendicular to the upper cross bars are present between main bars, spaced every 4" on center. The steel bars were connected to each other with the use of industry standard puddle welds (in accordance with AWS D1.5-95). The steel for the main bars, cross bars, and supplemental bars is ASTM A588, Grade 50. In addition, a 20-gauge concrete form pan, tack welded every 8" to the bottom flanges of the main bars, is used as stay-in place formwork.

Upon delivery of the grid deck specimens, it was discovered that a fabrication error had occurred in all four of the grid deck specimens. It was determined that during fabrication the lower cross bars had somehow been omitted. The lower cross bars are crucial because the 20-gauge concrete form pan does not offer adequate tensile reinforcement in a positive moment sense for weak direction bending in the deck system. The decision was made to keep the grid deck specimens and install the lower cross bars at the University of Pittsburgh, Watkins-Haggart Structural Engineering Laboratory. The lower cross bars consist of a #5 rebar placed perpendicular to the main bars. In order to install the lower cross bars, ¾" diameter holes are drilled in the main bars, spaced every 8" along the length of the grid deck specimen. The grid deck's fabricator developed a system for installing the lower cross bars. First, a template and center punch is used to mark the exact locations of the lower cross bars on the outside main bar. Next, a row of holes is drilled in the first main bar. Then, using the template and center punch, the holes are marked on the second main bar, and the second row of holes is then drilled. Once two rows of holes are established a 3' long drill bit is used to drill the remaining holes on the next three main bars (there are ten total main bars in each grid deck specimen, so five main bars are drilled from each side). The center punch and template will not be used on the remaining three main bars. The 3' drill bit passes through the first two holes in the main bars, restricting its movement, which means the drill bit was at the proper location for the next row of holes. The same procedure is used on the other side of the deck, beginning with the outermost main bar. Therefore, five main bars are drilled from each side. Next, the lower cross bars are then installed. The lower cross bars in most cases slipped right through the holes and into place. In some instances the rebar had to be forced through the width of the grid deck, by using a sledgehammer. The main reason the rebar (lower cross bars) had to be forced through is due to the fact that the holes are drilled from opposite ends of the grid deck. Due to the drill not being level, this caused changes in the elevation of the holes from the opposite sides. The lower cross bars are not welded or fastened in any way to the grid decks. The first grid deck specimen is then placed on the load frame (a description of the load frame will be provided subsequently) prior to drilling and installing the lower cross bars in order to save time.

2.2 Load Frame

Fatigue and ultimate strength tests will be performed on 20’ long by 6’ wide concrete filled grid deck specimens. The dimensions of the load frame are 34’ in length 8’ in width. The load frame is made of very large and heavy structural shapes. The purpose of the large members is to prevent the load frame from deflecting, which would impact the test data. The load frame consists of three major components. The first component of the load frame is two main beams, which provide support for the floor mounted reaction beams. The second component is the floor mounted reaction beams, which carry the roller supports. Next, the roller supports are oriented perpendicular to the 20’ length dimension of the grid deck specimen (i.e. perpendicular to the main bars). The last component is the loading system, which is comprised of columns, a loading crossbeam(s), and a hydraulic actuator(s). The load frame can be easily converted between the fatigue and ultimate strength test configurations. Drawings and pictures of the load frame are available in the appendices sections of this work.

The main beams, which lie on the floor, are made from two, 30 WF 172, 34' long. In addition, a 1" thick steel cover plate is welded to both the top and bottom flanges of the 30 WF 172's providing more stiffness. The main beams are connected to each other by three diaphragm members, 30 WF 172, 6' long, web bolted at each connection point, to full-depth stiffeners on the main beams. The shorter 30 WF 172 members are spaced every 12' along the length of the frame, starting at the middle of the load frame, and are fastened to the longer 30 WF 172 beams by using high strength bolts. In all of the 30 WF 172's there were 1" diameter holes spaced every 6" along their respective lengths. The holes are provided so that the reaction beams and columns can be secured properly.

Three reaction beams are used to support the specimens during both the fatigue and ultimate strength tests. These members support attachment points like the stringers of an actual bridge. The reaction beams at the ends of the grid deck specimen are identical consisting of two, 24 I 105.5 members, 10' long, are welded together. In addition, stiffeners are welded at 2.5' intervals along the reaction beams' length. To complete the reaction beam, 2.5" thick base plates are welded to the ends of the reaction beams. The reaction beams are then attached to the main beams (30 WF 172, 34' long) by the use of high strength bolts. The reaction beam at the middle is different however. It consists of a built up 24" deep member, which is 6' long. The built up member consists of 1" thick plates for both of the flanges as well as the web. The middle reaction beam also has stiffener plates which are ½" thick, and are welded to both flanges and the web. Four, 1-1/16" diameter holes were torch cut in the bottom flange of the built up member; it was secured to the middle 30 WF 172 with high strength bolts.

The roller supports, which are secured to the reaction beams, are different at each reaction beam location. The roller support at the northern edge of the grid deck consists of a LL 4"x4"x5/8", 7' long. The double angle is attached by high strength bolts to a 1" thick plate, which is welded to another 1" thick base plate, which is then bolted to the reaction beam. The southern support is a solid piece of steel stock, 6' long, beveled along the top surface, which acts as a knife-edge. The middle support is made from 1" diameter round stock. The 1" round stock is welded to a 2" x ¾" piece of bar stock, which is welded to a W8x69. The W8x69 and its appurtances were fabricated by Sippel Steel Company, and were donated for this research project. The W8x69 is then welded to the built up 24" deep reaction beam.

The final component of the loading frame is the loading system. The loading devices are two, 200 Kip actuators. Depending on the type of testing that was conducted, either one or two actuators are used. For the fatigue testing only one actuator, two columns, and one crossbeam are used in conjunction with a spreader beam. For the ultimate strength testing two actuators, four columns, and two crossbeams are used. The columns are 12 WF 85 with 15" x 22" x 2 ½" thick base plates.   The base plates are then attached to the main beams of the load frame by high strength bolts. The crossbeams are built up members, which form a box. The flanges are 1 ½" thick, and 7' long. The webs are ¾" thick, and 9' long. The webs extend past the flanges in order to overlap the column, and have 1” diameter holes in them, so the crossbeams can bolt to the columns. The overall depth of the crossbeam is 24” (See Appendix A for pictures of load frame).

The load frame supports (roller locations) are the same for the fatigue testing as well as the ultimate strength testing. The load frame is configured in the following manner for both sets of tests. Starting at the middle of the load frame, a floor reaction beam was secured to the load frame. Next, reaction beams are placed 10’ on center from the middle support in each direction. The supports are checked for levelness and are then shimmed if necessary. Next, a grid deck specimen is placed on the load frame, and checked for levelness. The only changes in the load frame occurred with the loading system, which is different between the fatigue and ultimate strength tests. A description of how both the fatigue tests and ultimate strength tests will be described in the subsequent sections of this work. Appendix A, and Appendix C contain both pictures as well as renderings of the load frame.

2.3 Instrumentation

Both the fatigue and ultimate strength tests are instrumented with three types of instrumentation: foil strain gauges; strain gauge rosettes; and Direct Current Displacement Transducers (DCDTs). Reference Appendix C, Figures C-4 through C-8 for a schematic of the instrumentation layout. Photographs of the DCDT and strain gauge setup are contained in Appendix A. The instrumentation is identical for both the fatigue and the ultimate strength tests.

The foil strain gauges are placed at the location of the middle support or at the mid span of each grid deck specimen. The foil strain gauges are placed only on the main bars of each grid deck specimen at three locations on each main bar. Gauges are placed at the top and bottom extreme fibers, as well at the midpoint of the web. The positioning of the foil gauges allowed the position of the strong-direction neutral axis to be monitored during testing. The foil strain gauge locations on the main bars are as follows: 1" on center from the top of the main bar; 3" on center from the top of the main bar; 4-3/8" on center from the top of the main bar (See Appendix C, Figure C-5 for the strain gauge layout). This was repeated on every other main bar, starting with the main bar located on the edge of the deck width. Therefore, 3 main bars are instrumented with foil strain gauges. Since the gauges have to be applied prior to concrete placement, each gauge is duplicated in case one was damaged during concrete placement. A 9-pin socket is then soldered to each strain gauge. The socket then connects to the data acquisition system

The strain gauge rosette is located at on one of the main bar punch-out locations. The strain gauge rosette is basically a three gauge assembly, with each gauge orientated at different angles: one gauge is orientated at 0 degrees, while the other two gauges are orientated 45 degrees from the horizontal axis. The strain gauge rosette is used to calculate the principal stresses in the area of the punch-out. The rosettes are also connected to the data acquisition system via the 9-pin socket adapter. See Appendix C, Figure C-5, and Figure C-8 for the strain gauge rosette location and description.

The final component of the instrumentation package is the DCDTs (Direct Current Displacement Transducer). These transducers are positioned on the underside the grid decks using fabricated stands. The DCDTs are located 3' on center on either side of the middle support (DCDTs are in the loading plane). The DCDTs are located as follows: the outside main bar, 16" from the first main bar, then 16" from the second main bar (i.e. every other main bar until the mid width of the grid deck is reached). Therefore three DCDTs are located on the north span and three DCDTs are located on the south span. The transducers are then connected via a magnet to respective main bar that is instrumented with strain gauges (see Appendix C, Figures C-4 through C-8, for the DCDTs locations). The DCDTs have a captured armature core with a threaded top that allowed for the use of an attachment nut. A U-shaped magnet is used to hold the DCDT to the underside of the grid deck. The magnet has a hole drilled in it to allow for the core of the DCDT to extend through the magnet. The hole is made oversize so as to accommodate rotation of the specimen during testing could be accommodated without damaging the captured armature core. The DCDTs are removed at a predetermined load point during the ultimate strength testing so as to protect them from damage. The DCDTs are then wired to a bus bar, which provides electric power to the transducers. The bus bar is then wired to 9-pin socket adapter, which is connected to the data acquisition system.

2.4 Fatigue Testing

2.4.1 Overview of Fatigue Testing

Fatigue testing will be carried out using two specimens that are identical in overall geometry, as well as being instrumented identically. The only difference between the two fatigue specimens is the loading protocol followed during their testing (the loading protocol will be described in the subsequent sections of this work). In both cases, the loading of the fatigue specimens is carried out with a single hydraulic actuator attached to a spreader beam that in turn provided loading consistent with the axle load of the design truck considered in the individual test. The spreader beam is used to split the load from the hydraulic actuator and transfer it to two 8”x20” steel plates spaced 6’ out-to-out. This loading arrangement is consistent with the tire spacing and equivalent tire contact area for the AASTHO design truck.

Fatigue Specimen #1 is tested in a way, which is consistent with an HS-20 design truck loading. The peak load level, at each tire contact point, achieved during a given cycle is based on the design loads contained in Section 3 of the AASHTO LRFD Bridge Design Specifications. Based on these provisions, the 16 Kip HS-20 tire loading is multiplied by a load factor of 0.75 (as per Table 3.4.1-1) and an impact factor of 1.15 (as per Table 3.6.2.1-1) resulting in a tire patch load of 13.8 Kips. This is then subsequently amplified by a “PA traffic factor” of 1.2 thus resulting in the tire load of 16.6 Kips that is subsequently used as the peak load for each cycle of testing. Hence the loading of Fatigue Specimen #1 is based on a sinusoidally varying loading function whose peak tire load value is 16.6 Kips and whose minimum tire load value is approximately 0.5 Kips. Since earlier research (Mangelsdorf, 1996 and Mertz & Jurkovic, 1996) indicates that it is conservative to consider concrete filled grid deck as Fatigue Category “C” (AAHSTO LRFD Table 6.6.1.2.5-3), a check of the design fatigue loading described above is carried out within the context of the AASHTO LRFD design provisions related to the strength of concrete filled steel grid deck (AASHTO LRFD Section 4.6.2.1.8). From this calculation it appears that a 16.6 Kip peak load would result in a maximum extreme fiber stress of 17 Ksi, which is greater than the 10 Ksi endurance limit associated with Fatigue Category "C". Despite this finding, testing of Fatigue Specimen #1 was carried out using the 16.6 Kip tire loading. Since earlier research indicates that the deck specimens qualify as Fatigue Category "C", or better, it is felt that the survival of Fatigue Specimen #1 for 5,000,000 cycles of the design truck would ensure infinite fatigue life under field conditions since, as pointed out earlier, the stress range during testing should exceed the endurance limit for Fatigue Category "C" (the worst case classification for filled grid deck) and hence attainment of 5,000,000 cycles would clearly support the infinite fatigue life claim.

Fatigue Specimen #2 is tested according to ASTM D 6275-98. The ASTM standard calls for the same loading configuration used in Fatigue Specimen #1 testing, but requires a much greater peak tire load (20.8 Kips) for fewer cycles (2,000,000). A deviation from the ASTM standard occurred in that the tire loading is increased to 26 Kip (a value consistent with an HS-25 design truck). The 26 Kip wheel load is determined by multiplying the ASTM standard specified value of 20.8 Kips, times the ratio of 25/20. This ratio is the gross weights of the respective design trucks in tons.

For this project the concrete specified is PennDOT AAA, f'c = 4500 psi (28 day concrete compressive strength), max 3/8" aggregate. Two separate concrete placements were performed when fabricating the test specimens. The first fatigue specimen was done on the first placement. In order to save time the remaining fatigue specimen and the ultimate strength specimens were poured on the same day (the ultimate strength tests will be described later in the research). The concrete was delivered to the lab in a ready-mix truck. The concrete was then collected in a concrete bucket and hauled to the grid deck using an overhead crane. The concrete was placed into the grid deck and formwork, and vibration was performed to ensure that the concrete contained no voids. On the day of the pour form oil was used on the formwork, being careful not to place any form oil on the steel of the grid deck. The concrete was then screeded, finished with a flat trowel, and allowed to air dry for no less than 28 days. The formwork was removed three days after placing the concrete.

The loading system is next to be set up. The loading set up is the same for both fatigue specimens. Two 8”x20” steel plates are set on the finished deck in order to provide a contact area consistent with the tire patch of the design truck. Next, a spreader beam is set on top of the steel plates, and then the spreader beam is attached to a hydraulic powered actuator, which is what applies the loading. The details of the loading system are contained in subsequent sections of this research.

The final step is to place the DCDTs, at the designated locations underneath the grid deck specimen. The foil strain gauges, along with the DCDT s, are connected to a MicroMeasurements System 5000 Data Acquisition System.

This setup completes the preparation needed for the execution of the fatigue tests. Reference the final subsection of the Fatigue Tests for a complete description of the Testing Protocol.

2.4.2 Description of Loading System

The fatigue tests are done in order to simulate wheel loadings from an AASHTO design truck. Two, 2" thick, 8"x20" steel plates represent an approximate tire contact area, as prescribed in the AASHTO specification (the AASHTO contact area varies with loading intensity and hence would be variable). Two W10x45's connected the two plates to a W24x76 spreader beam. The spreader beam and the W10x45's are both stiffened, to ensure that there would be no deflections due to the fatigue loading. A 1" thick steel plate is welded to the top of the W24x76 spreader beam for attachment to the actuator. The steel plate is 12" x12" with 1" diameter holes so that it could be bolted to the hydraulic actuator. A ½" piece of round stock is welded to the top of the spreader beam, to act as a pivot point, to protect the piston against bending.

The actuator loading system consists of a 12"x12" steel plate (a foot), which has a 3-1/4" diameter threaded, 3" tall collar welded to the plate. This threaded collar is then stiffened with ½" thick steel plates. A 3 ¼" diameter, 3" long all-thread was then threaded into the collar of the base plate at one end. The all-thread and foot is then threaded into a 200 Kip pancake load cell. The pancake load cell then threads onto the piston of the hydraulic powered actuator. The actuator is bolted to a 1 ¾" thick steel adapter plate. The adapter plate then clamps to the bottom flange of the cross beam by two additional 1 ¾" thick steel plates.

An MTS 458 controller and micro-profiler controlled the hydraulic actuator. The micro-profiler generated the cyclic loading function for the fatigue tests; a sinusoidal loading function with a frequency of 5 Hz. The MTS 458 controller is then connected to an oscilloscope, which plotted the loading function in real time. Each fatigue specimen's loading will be subsequently detailed.

2.4.3 Fatigue Specimen #1

Fatigue specimen #1 was the first grid deck specimen to be tested. Fatigue Specimen #1 is placed on the load frame (prior to concrete placement); the lower cross bars and foil strain gauges are installed. The deck is then cleaned of debris using compressed air. Next, the concrete is placed, and allowed to air dry for no less than 28 days. The 28-day concrete compressive strength for this fatigue specimen is 6354 psi, which is obtained by using the average strength of 8 cylinder tests. The servo-controlled hydraulic actuator produced 33.2 Kips of load, cycled 5,000,000 times at 5 Hz.

Prior to the start of fatigue testing, a static test is performed in order to establish a benchmark of both deflection and strain values. The static test consists of loading the specimen from 0 Kips to 35 Kips in 5 Kip increments. At each increment of loading data is acquired using both the System 5000, and the Strain Smart Data software. Once the benchmark specimen response values are established, the fatigue test can be started. At the start of each day of the fatigue testing, the spreader beam is checked for levelness, and the steel plates are shimmed when necessary. The loading program is then entered and stored in the MTS 458 controller and micro-profiler, and the program was started. By using the span control knob on the MTS 458 controller, and the oscilloscope, the sinusoidal loading function can be adjusted until the sine wave reaches the proper amplitude on the oscilloscope.

The fatigue test is started every morning and allowed to cycle 150,000 cycles during the day. The MTS 458 micro-profiler is programmed to run 150,000 cycles of load and then shut down. It will take approximately 8.5 hours to apply the 150,000 cycles of load. A static test can then be performed after each day of testing (i.e. every 150,000 cycles). The static test is carried out in order to observe any degradation in stiffness of the grid deck, due to the day-to-day fatigue testing. In addition, a visual inspection will be performed daily so as to identify any physical changes in the grid deck, such as a crack in the concrete, or in the steel of the main bars. Since only 150,000 cycles are applied daily, it will take approximately 33 days to perform the entire 5,000,000 cycles of load.

2.4.4 Fatigue Specimen #2

In order to save time on the overall project, the remaining fatigue specimen, and the two ultimate strength specimens will be poured prior to being placed on the load frame. The preparatory work, as well as the concrete placement, will be done while the first fatigue test is being conducted. The lower cross bars are first installed, and the grid deck can then be instrumented with 18 foil strain gauges. Next, four stay-in place lifting lugs are installed so that the concrete filled grid deck can be easily lifted onto the load frame without damaging the specimen. The lifting lugs are made from ½” thick steel plate, and are torch cut to fit between two upper cross bars, as well notched on the bottom to fit over the bottom cross bar. A 1” diameter hole is also flame cut in order to attach the clevis to the lifting lug. The lifting lugs were located 5’ from both ends of the grid decks' long dimension, and 10" from the edge of the grid deck. Next, the deck is cleaned of debris using compressed air. Finally the deck is formed and the concrete is then placed, and allowed to air dry for no less than 28 days. The grid deck is lifted onto the load frame by attaching a clevis on each of the four lifting lugs. Next, two chain spreaders are looped through the clevises and then attach to the lifting beam. A 10' long lifting beam is hooked to the crane and the grid deck specimen is then placed onto the load frame, being careful not to damage the specimen in any way.

The concrete strength of Fatigue Specimen #2 is 6218 psi, which is obtained by taking the average of 12 cylinder tests (the remaining 3 decks were poured on the same day; therefore it is necessary to perform more cylinder tests). Fatigue Specimen #2 is tested according to ASTM D 6275-98, which specifies a wheel load of consistent with a HS-20 design truck. A decision was made to test Fatigue Specimen #2 as an HS-25 design loading, which made the wheel loadings 26 Kips at each tire contact area. Therefore the servo-controlled actuator will produce 52 Kips of loading, cycled 2,000,000 times at 5 Hz. A static test is done prior to any testing in order to establish a benchmark of both deflection and strain values. The static test consists of loading the specimen from 0 Kips to 50 Kips in 5 Kip increments. At each increment of loading data is acquired using both the System 5000, and the Strain Smart Data software. Once the benchmark specimen response values are established, the fatigue test is then started. At the start of each day of testing the spreader beam is checked for levelness, and the steel plates are shimmed if necessary. The loading program is then entered and stored in the MTS 458 micro-profiler, and the program is started. By using the span control knob on the MTS 458 Controller, and the oscilloscope, the sinusoidal loading function is adjusted until the sine wave reaches the proper amplitude on the oscilloscope.

The fatigue test will be started every morning and allowed to cycle 150,000 cycles during the day. In the same manner as Fatigue Specimen #1, the MTS458 micro-profiler is programmed to run 150,000 cycles of load and then shut down. Again it took approximately 8.5 hours to apply 150,000 cycles of load. Similar to Fatigue Specimen #1, a static test will be done after each day of testing (i.e. every 150,000 cycles) in order to monitor any changes in the grid decks stiffness. Also, a visual inspection was performed daily so as to identify any cracks in the concrete or in the main bars of the grid deck. Since only 150,000 cycles are applied daily, it will take approximately 16 days to perform the entire 2,000,000 cycles of load.

2.5 Ultimate Strength Testing

2.5.1 Overview of Ultimate Strength Testing

Ultimate strength tests will be carried out on all four concrete grid deck specimens. The ultimate strength testing is performed on two grid decks that will not be cycled for fatigue, and on the two grid decks that will be cycled for fatigue. The ultimate testing is done in order to better understand what kind of failure is to be expected with the grid decks, and at what loading these grid decks would fail.

The first set (virgin decks) of ultimate strength tests are tested after 28 days of the concrete placement. The virgin grid deck specimens are prepared in a similar manner as the second fatigue specimen. The grid deck specimens have the same dimensions as well as the same geometry and element dimensions as those that will be tested for fatigue.

In order to save time on the overall project schedule, it was decided to prepare the remaining grid deck specimens, while the test on Fatigue Specimen #1 was being conducted. The grid deck's missing lower cross bars are first installed. Next, the bonded foil strain gauges are placed at the designated locations on the main bars. Since the concrete is going to be placed prior to the decks being placed on the load frame, four lifting lugs are then installed in the grid decks at the same locations as those on Fatigue Specimen #2. The grid decks are then cleaned of debris using compressed air. Next, formwork is installed and the concrete is then placed in the same manner as the fatigue test.

Finally the ultimate strength specimen is placed on the load frame. The ultimate strength specimens used the same methodology that was used to lift Fatigue Specimen #2 onto the load frame. During the lifting of the grid decks extra care will be taken so that the grid deck specimen is not damaged.

The loading system is next to be set up. For the ultimate strength tests two steel plates are placed on the finished deck. Next, two servo-controlled, 200 Kip capacity actuators are then lowered onto the steel plates. There were only minor variations in the loading system between the first set of ultimate tests and the second set of ultimate tests. These differences will be described in the subsequent sections of this research.

Once the ultimate strength specimen was placed on the load frame, the final step is to place the DCDTs, at the previously specified locations underneath the grid deck specimen. The foil strain gauges along with the DCDTs are then connected to the MicroMeasurements System 5000 Data Acquisition system, which was the same set up as the fatigue specimens. This set up completes the preparation needed for the execution of the ultimate strength tests. Reference the final subsection of the Ultimate Strength Tests for a complete description of the testing protocol.

2.5.2 Description of Loading System

For the first set of ultimate tests, two, 2” thick, 8” x 20” steel plates represent a HS-20 tire patch. The steel plates are placed at a distance of 3’ on center from the middle support, and a distance of 3’ on center from the edge of the finished grid deck. Next, two 200 Kip, hydraulic powered actuators are then installed over the locations of the steel plates.

The actuator loading system consisted of the same 12”x12” stiffened steel plate, which acts like a foot. The actuators are then secured to the cross beams of the load frame by a 1 ¾” thick steel adapter plates. The steel plate is then bolted to the actuator. The adapter plate then clamps to the bottom flange of the cross beams by two additional 1 ¾” thick steel plates.

The MTS 458 micro-profiler is used to ramp the load from zero to the ultimate value. For the ultimate strength tests, the loading will be applied at a rate of 1Kip every 10 seconds. The program drove both actuators simultaneously, thereby delivering the same load at the same time. At a previously determined load the loading program is suspended so that the DCDTs can be removed so that they were not damaged from falling debris from the failing grid deck.

2.5.3 Ultimate Strength Specimens #1 & #2

Ultimate Strength Specimens #1 & #2 are the first set of ultimate tests that are conducted; these deck specimens will not be part of the fatigue-testing program. One of the ultimate strength test specimens is lifted into place on the load frame, being careful not to damage the specimen in any way. The loading system for this test simply consists of the steel plates and the actuators.

Also, f'c = 6218 psi (28 day concrete compressive strength) for both of these ultimate strength specimens, since they were poured on the same day. Next, the actuators are lowered on to the steel plates, and then the loading program can begin. The ultimate strength testing will be run in load-control using the MTS 458 controller and micro-profiler. The Data Acquisition System is then set to acquire data every 10 seconds to match the load that is being applied quasi-statically at a rate of 1 Kip every 10 seconds. When the specimen reaches 60 Kips (on each actuator) the loading program will be suspended, and the DCDT s will be removed. Once the DCDTs are removed, the load program can then be restarted, and will then be loaded to failure (while the loading is suspended the Data Acquisition System, kept acquiring data, once the loading is restored, a note was made of which data increment the loading was restarted on). Once failure is observed, the peak value will be noted, and the loading system shut down.

2.5.4 Ultimate Strength Specimens #3 & #4

Ultimate Strength Specimens #3 & #4 varied slightly than the previous set of ultimate tests. Ultimate Strength Specimen #3 was the former Fatigue Specimen #2 that had been cycled 2,000,000 times, and Ultimate Strength Specimen #4 was the former Fatigue Specimen #1 that was cycled 5,000,000 times. In addition, the 28-day concrete compressive strength for Ultimate Strength Specimen #3 is 6218 psi, and the 28-day concrete compressive strength of Ultimate Strength Specimen #4 is 6354 psi. No instrumentation will be used during these sets of tests; only the peak load is of value here. The loading system will be adjusted, due to observations made during the first two ultimate strength tests. The change in the loading system consisted of the addition of a 2" diameter, 12" long piece of round stock, which was welded to the steel plates, perpendicular to the plate's 20" long dimension. This provided a pivot point which allowed the 8"x20" plate to rotate as the deck deflection increased.

These ultimate strength tests will be done in the same way as the ultimate tests that were previously described. The only difference is that there will be no instrumentation used in Ultimate Strength Specimens #3 & #4. The values determined by performing the ultimate strength tests will help determine if there was any damage done to the main bars during the fatigue loading. A comparison can then be made in the peak loading between the two virgin decks and the two fatigued decks.

3.0 DISSCUSSION OF THE RESULTS

The results from the data acquired from both the fatigue and ultimate strength tests are interpreted and discussed in this section. Data from the foil strain gauges and the DCDTs were reduced and plotted to monitor the grid decks' response during both fatigue and ultimate strength testing. The parameters that provide the most useful information are the measured main bar stiffness, the strong-direction neutral axis location at the main bar locations, and the deflection profiles across the deck width at the cross-section corresponding to the load points. Appendix D contains Table D-3 and Table D-5, which are tabulations of the main bar stiffness (in Kips/inch) values for both Fatigue Specimen #1 and Fatigue Specimen #2, respectively. Also included on these tables are the percent of benchmark, which is the new stiffness value, divided by the benchmark value, times 100. The dashed lines in the tables indicate that a DCDT has malfunctioned since data could not be obtained. The deflection data is used to monitor any change in stiffness at discrete points during the cyclic loading of the two fatigue specimens as well as the overall deck response during the ultimate strength testing. The cross-sectional strain distribution and neutral axis locations are graphed in order to monitor any change in the section properties of the grid deck during testing. The strain gauge rosette values are tabulated in Appendix D for both the fatigue and ultimate strength tests (rosettes are positioned to enable a determination of the stress at the punch-out locations).

The fatigue test data is reduced from static tests that are performed on the fatigue specimens after every day of testing (each day of testing resulted in 150,000 cycles of loading). The main bar stiffness values are obtained by using the reduced data of an initial, or benchmark response values from a static test prior to any cyclic testing. The stiffness values are based on the initial slope of the load deflection response. Table D-3 and Table D-5 in Appendix D, contains the main bar stiffness values for both Fatigue Specimen #1 and Fatigue Specimen #2, respectively. The slope of the line obtained from a liner regression analysis, forced through the zero point, is to obtain the main bar stiffnesses. The graphs of the load-deflection response are located in Appendix B: Figures B-1 through B-105 corresponds to the response of Fatigue Specimen #1; Figures B-246 through B-287 correspond to the response of Fatigue Specimen #2. The load-deflection graphs are plotted for each instrumented main bar, for each day of fatigue testing. Two plots appear on each graph, one for the north span and one for the south span of the same main bar. In most instances the load-deflection graphs are linear, but some graphs are not linear or instrumentation malfunctions prohibited the drawing of a plot.

While Fatigue Specimens #1 and #2 are also tested to ultimate, it is only Ultimate Strength Specimen #1 and Ultimate Strength Specimen #2 where the instrumentation data (besides the peak load) is acquired. The load-deflection responses for the ultimate strength specimens are plotted by span; therefore there are three plots on one graph (the three DCDTs on each span are plotted on one graph). Appendix B contains graphs for the ultimate strength test specimens, Figures B-372 and B-373, and Figures B-382 and B-383 show the load-deflection response for Ultimate Strength Specimen #1 and Ultimate Strength Specimen #2 respectively. The deflection profiles across the deck width are also plotted by span for both Ultimate Strength Specimen #1 and Ultimate Strength Specimen

#2, and are shown in figures B-374 through B-375 and B-384 through B-385, respectively. The DCDTs are removed when each actuator reaches 60 Kips, during Ultimate Strength Specimen #1, and when 70 Kips is reached for each actuator during Ultimate Strength Specimen #2. This is done to protect the DCDTs from damage. The deflection profile was also plotted for the ultimate strength specimens, which is a plot of vertical deflection at points along deck width corresponding to the loaded cross-sections in the north and south spans.

The cross-sectional strain distributions are then plotted for both the fatigue and ultimate strength tests. The neutral axis graphs are plotted for the steel main bars only; not for the concrete overfill. It is assumed that, since the concrete is in tension over the middle support, the concrete is ineffective, since it has cracked. The graphs are determined by plotting the height from the top of the main bar versus the strains in the main bars (micro-strains, $\mu\varepsilon$) at both the top (tension) and at the bottom (compression) of the main bar. The neutral axis can then be determined from the cross-sectional strain distribution graphs, by identifying the point of zero strain for each load and noting the corresponding height from the top of the main bar. Upon obtaining the neutral axis from the cross-sectional strain distribution graphs, a plot is subsequently made by plotting the height of the neutral axis from the top of the main bar versus the load level. This graph displays any change in the neutral axis location as a function of the loading applied. The cross-sectional strain distribution and the neutral axis graphs are located in Appendix B, Figures B-106 through B-245 for Fatigue Specimen #1; Figures B-288 through B-371 for Fatigue Specimen #2; Figures B-376 through B-381 for Ultimate Strength Specimen

#1; Figures B-386 through B-391 for Ultimate Strength Specimen #2. For the fatigue tests, the strain distribution as well as the neutral axis positions for each instrumented main bar is determined for everyday of testing. The load range for the static test conducted in conjunction with Fatigue Specimen #1 is from 0 to 35 Kips (in 5 Kip increments) and the load range for the static test conducted in conjunction with Fatigue Specimen #2 was from 0 to 50 Kips (also in 5 Kip increments). The cross-sectional strain distribution for each main bar was plotted in 10 Kip increments for the two instrumented ultimate strength tests, up to the peak loading. The peak loads for all four of the ultimate strength test specimens are tabulated in Appendix D, Table D-6.

The strain gauge rosette values are tabulated for each day of fatigue testing in the fatigue specimens, and up to the peak value (in 10 Kip increments) for the ultimate strength specimens. The rosettes are labeled Strain Gauge #19, Strain Gauge #20, and Strain Gauge #21; this is typical for both the fatigue and ultimate strength testing. The strain values that are measured by the rosettes are small in comparison to longitudinal strains the strains that occur over the middle support in the negative moment region. The strain gauge rosette values will be reported in Appendix D, Table D-2 for Fatigue Specimen #1; Table D-4 for Fatigue Specimen #2; Table D-7 for Ultimate Strength Specimen #1; Table D-8 for Ultimate Strength Specimen #2.

3.1 Fatigue Specimen #1

Fatigue Specimen #1 logged 5,000,000 cycles of a sinusoidally varying load with a peak amplitude corresponding to a 16.6 Kips wheel load (based on an AASHTO HS-20 tire loading, which also includes a “PA Traffic Factor”). For the first 1,200,000 cycles of load, the stiffness actually increased anywhere from 115% to 135% of the benchmark value. Once 1,350,000 cycles is reached, the stiffness values remain relatively constant up to 3,150,000 cycles where the benchmark values are at least 120% of the benchmark value. The stiffness values then drop between 100% and 105% of the benchmark value, during the interval from 3,150,000 cycles to 4,200,000 cycles. At 4,200,000 cycles the stiffness begins degrading rapidly to roughly 75% of the benchmark value. Also, at 4,200,000 cycles it is visibly noticeable that the grid deck began to deflect more during the cyclic loading than at any other time. The stiffness values then steadily decrease during the remaining cycles of loading up to the 5,000,000 cycles. At 5,000,000 cycles of load the stiffness values of the main bars is measured to be between 40% and 50% of the benchmark values.

While attempting to plot the cross-sectional strain distribution graphs for Main Bar #3, it was noticed that only one of the six strain gauges survived the concrete placement despite the fact that each gauge was duplicated at each location on every instrumented main bar (to help guard against a total loss of instrumentation on a given main bar), but only one strain gauge (#13) was working. Hence, for Fatigue Specimen #1, only cross-sectional strain distributions and neutral axis locations for Main Bar #1, and Main Bar #2 are available. The surviving strain gauge on Main Bar #3, which is located at the top of the main bar, is in the tension zone. The output from strain gauge #13 is tabulated in Appendix D, Table D-1, for everyday of testing (or every 150,000 cycles). Throughout the entire 5,000,000 cycles of load, the neutral axis locations for the main bars remained roughly in the same locations (with only slight deviations). The theoretical neutral axis was calculated using the BGFMA Technical Data Sheet on grid deck section properties (BGFMA, 1997). BGFMA assumes that a ½" of the concrete overfill is sacrificial; therefore it is subtracted out when calculating the neutral axis. Since the main bars of the grid deck specimens are spaced 8" on center, it is assumed that the effective concrete width is 8" (4" on each side of a typical main bar). Using the modular ratio of the concrete and steel, the concrete is transformed into steel. The calculated theoretical neutral axis value is 2.75" from the top of the main bar. The experimentally obtained neutral axis values are 3" for Main Bar #1, and 3.5" for Main Bar #2, both distances are from the tops of the respective main bars. When graphing the cross-sectional strain distributions, all of the strain values pass through a zero point, at nearly the same location (i.e. neutral axis position is static during loading). This is true until the grid deck reaches 4,200,000 cycles of loading. Conversely at 4,200,000 cycles, the cross-sectional strain distribution graphs become very widely scattered about the zero strain line, i.e. the neutral axis position shifts with the load level (See Appendix B, Figures B-220 through B-245). Also, at 4,200,000 cycles of load, strain gauge #13 on Main Bar #3, (which is the main bar directly under the loading) jumps by 50 micro-strains ($\mu\varepsilon$) from 160 $\mu\varepsilon$ to 209 $\mu\varepsilon$, the average strain was 165 $\mu\varepsilon$ throughout the entire fatigue testing until this point. Just 150,000 cycles later (4,350,000) the strain jumps another 55 $\mu\varepsilon$ to 266 $\mu\varepsilon$, which is its last reading. Strain gauge #13 went off line after the 29th day of testing (i.e. after 4,350,000 cycles).

From the results discussed above, it appears that the concrete started debonding from the steel grid work at 4,200,000 cycles of load and debonding continued during the remainder of the 5,000,000 cycles of loading. The evidence supporting the hypothesis of concrete debonding emanates from three main observations:

1. The main bar stiffness values changed suddenly at 4,200,000 cycles and continued to degrade to 40% to 50% of the benchmark values during the remainder of the 5,000,000 cycles of loading.
2. The cross-sectional strain profiles, which had displayed a static neutral axis location during loading, began displaying significant scatter, which continued to the end of testing (the neutral axis shifted downward with the increasing load, thus indicating the lack of concrete participation).
3. Strain gauge #13 located on Main Bar #3, began to register large strain increases starting at 4,200,000 cycles and continued until it went off line. The debonded concrete sliding back and forth along the main bar could be what caused damage to the gauge during the cyclic loading.

The stresses in the main bars were calculated at the final 5,000,000 cycles of loading in order to compare the stresses in the main bars to the fatigue threshold stress of 10 Ksi. The stresses in the main bars are as follows: Main Bar #1, 4.40 Ksi; Main Bar #2, 8.60 Ksi. The stress in Main Bar #3 could not be calculated directly due to the fact that the remaining strain gauge stopped working after 4,350,000 cycles. The stress at 4,350,000 cycles for Main Bar #3 is 7.70 Ksi. The stress in all of the main bars begins increasing at this point due to the fact that the grid deck is losing its stiffness due the debonding of the concrete (i.e. the steel was taking more of the load). Upon comparing the strains of all the main bars for each day of testing it is observed that the strain values are basically constant for equivalent load levels achieved during the static tests carried out at the end of each day of testing until the 4,350,000 cycles is achieved. Based upon this repeatability, an approximation to the stress in Main Bar #3 can be calculated, from the ratio of the stresses in the other instrumented main bars. The maximum tensile stresses at 4,350,000 cycles for Main Bars #2 & #3 are 6.60 Ksi and 7.70 Ksi, respectively. The maximum tensile stress at 5,000,000 cycles for Main Bar #2 is 8.60 Ksi. Using the ratio of 6.60 Ksi/ 7.70 Ksi (stress of Main Bar #2/stress Main Bar #3) at 4,350,000 cycles equals to 8.60 Ksi/ X (stress of Main Bar #2/ unknown stress of Main Bar #3) at 5,000,000 cycles, yields X = 9.95 Ksi in Main Bar #3. Therefore, even after concrete debonding, the maximum longitudinal stresses are less than the 10 Ksi threshold of the AASHTO, Fatigue Category "C" stress.

3.2 Fatigue Specimen #2

Fatigue Specimen #2 logged 2,000,000 cycles of a sinusoidally varying load with a peak amplitude corresponding to a 26 Kips wheel load (based on a ratio of AASHTO HS-20/HS-25 tire loading). The same methodology for the data reduction that was used in Fatigue Specimen #1, is used with Fatigue Specimen #2, where the benchmark data is first collected prior to any cyclic loading being conducted. For the first 1,050,000 cycles of load, the stiffness of the main bars increased between 115% and 120% of the benchmark value. During the interval between 1,050,000 cycles and 2,000,000 cycles of load the stiffness values remained constant with the stiffness values ranging between 115% and 130%, depending on the main bar. At 2,000,000 cycles of load the stiffness values of the main bars is measured between 115% and 120% of the benchmark values. The DCDTs on Fatigue Specimen #2 produced favorable results throughout the entire 2,000,000 cycles of loading.

The cross-sectional strain distribution graphs for determining the neutral axis location were calculated using the same methodology that was used for Fatigue Specimen #1. Throughout the cyclic loading of Fatigue Specimen #2, the cross-sectional strain plots show the strain distribution to intersect the zero strain line at the same point for all of the loads. The experimental neutral axis for Main Bar #1 is approximately 3.5”, for Main Bar #2 it is approximately 4”, and for Main Bar #3 it is also approximately 4”.

From the results obtained for Fatigue Specimen #2, it appears that no damage has occurred to Fatigue Specimen #2 due to the 2,000,000 cycles of amplified HS-25 wheel loading. The stiffness values of the instrumented main bars actually increase during the 2,000,000 cycles of loading. Also, there are no visible changes in the grid decks behavior during the fatigue testing. The graphs of the cross-sectional strain distribution only vary a small amount around 1,700,000 cycles (nothing would indicate that debonding has occurred). Upon comparing the strains of all of the main bars for each day of testing it is observed that the strain values are basically constant for equivalent load levels achieved during the static tests carried out at the end of each day of testing. The stresses in the main bars of Fatigue Specimen #2 at 2,000,000 cycles are as follows: Main Bar #1, 5.30 Ksi; Main Bar #2, 5.20 Ksi; Main Bar #3, 6.0 Ksi. The stress values of Fatigue Specimen #2 are indeed lower than the 10 Ksi fatigue threshold as specified in the AASHTO code.

3.3 Ultimate Strength Specimen #1

The deflection profile of Ultimate Strength Specimen #1 for both the north and south spans displays an essentially linear response. It is important to note that the DCDTs are removed once 60 Kips is reached on each actuator, so as to protect the DCDTs from being damaged. When plotting the cross-sectional strain distribution through the depth of an instrumented main bar it is interesting to note the high strain values obtained in the negative moment region over the middle support. The cross-sectional strain distribution plots for Main Bar #1 and Main Bar #3 display a static neutral axis location during the ultimate loading. Main Bar #2 however, displays significant scatter, thus the neutral axis location begins shifting downward with the increasing load, which is an indication the lack of concrete participation (See Appendix B, Figures B-376 through B-381, for the graphs of the cross-sectional strain distribution).

During the testing of Ultimate Strength Specimen #1 it is noted that the deflection of the grid deck specimen along its length is symmetrical between the north and south spans. The peak load for Ultimate Strength Specimen #1 is 126 Kips. At this load a loud bang occurred, and the deck suddenly deflected an extensive amount. It was assumed at that point that plastic hinges had formed and the deck had collapsed, hence the load was taken off of the grid deck. When the load was removed, the deck rose back up almost to its initial height. The only visible damage was a negative moment crack in the concrete over the length of the entire middle support as well as a slight kink in the steel, at the middle support. At the peak load, the maximum strain in the most highly stressed main bar is equal to 1608 $\mu\varepsilon$, which corresponds to a stress of 46.63 Ksi, a value that is less than the yield stress of the steel, which is 50 Ksi. Based on the loud bang and the lack of main bar yielding over the middle support, it appears that a sudden loss of composite action between the steel grid work and the concrete precipitated the failure.

3.4 Ultimate Strength Specimen #2

The data was reduced for Ultimate Strength Specimen #2 and the same graphs are plotted as in Ultimate Strength Specimen #1. The cross-sectional strain distribution plots for Main Bar #1 displays significant scatter, which indicates that the neutral axis location is shifting downward with the increasing load. However, the plots for Main Bar #2 and Main Bar #3 display a static neutral axis location during the loading. (See Appendix B, Figure B-386 through B-391, for the graphs of the cross-sectional strain distribution). The deflection profile of Ultimate Strength Specimen #2 exhibit deflection results that one would not typically expect to obtain theoretically. The deflection results from this test are very difficult to interpret due to a problem that occurred during the casting of the specimen. During casting, some concrete seeped out of the forms on the south end of the specimen thus creating a lip that prevented the main bars from making contact with the end support. This lack of contact was only present along a portion of the deck width at the south span and thus resulted in the deck being twisted about its long axis. The cause of failure this time was the fact that the steel yielded. The peak load of 83 Kips is recorded. At 83 Kips, the maximum strain is 1860 $\mu\varepsilon$ in Main Bar #3, which produced a stress of approximately 54 Ksi, so it is clear to see that the steel certainly has yielded.

3.5 Ultimate Strength Specimen #3 & #4

Ultimate Strength Specimen #3 is the former Fatigue Specimen #2 (i.e. Ultimate Strength Test #3 was carried out on Fatigue Specimen #2 after the completion of the 2,000,000 cycles), and Ultimate Strength Specimen #4 is the former Fatigue Specimen #1 (i.e. Ultimate Strength Test #4 was carried out on Fatigue Specimen #1 after the completion of the 5,000,000 cycles). Ultimate Strength Specimen #3 displayed an asymmetrical deflection about the center support, with the south span deflecting more than the north span. The grid deck specimen was loaded until the peak value of 73 Kips where upon a collapse mechanism formed in the south span.

Ultimate Strength Specimen #4 was the final grid deck specimen to be tested. This grid deck specimen was previously loaded 5,000,000 times, and it was clear that there was already some damage done to the specimen during the fatigue loading process. Ultimate Strength Specimen #4 displayed an asymmetrical deflection about the center support, with the south span deflecting more than the north span. The grid deck specimen was loaded until the peak value of 70.10 Kips whereupon a collapse mechanism formed in the south span.

4.0 CONCLUSIONS

Based on the research reported herein, concrete filled grid deck with a 10’ span is both a safe and a viable option for use on bridge decking and re-decking operations. The PennDOT BD-604 is indeed conservative in the span length for concrete filled grid decks with 5-3/16” deep main bars, spaced 8” on center; one supplemental bar; and a 1 ¾” concrete overfill. Currently, the PennDOT BD-604 limits the use of such a deck to a maximum span of 6’ between supports.

The data did however show some degradation in stiffness for Fatigue Specimen #1. This stiffness reduction can best be explained by the fact that the concrete may have started to debond from the steel at 4,200,000 cycles of loading. Prior to 4,200,000 cycles, the stresses in the main bars remained relatively constant. After 4,200,000 cycles however the deflections grew, along with the stresses in the main bars. Under the action of a 16.6 Kip wheel load, a max flexural longitudinal stress of 9.95 Ksi was calculated to be in Main Bar #3 at 5,000,000 cycles. Clearly the stress of 9.95 Ksi is under the 10 Ksi threshold specified by AASHTO Fatigue Category “C”. Fatigue Specimen #1 was well under the maximum deflection limit of L/1000 (0.12 in) as stated in the AASHTO-LRFD design manual at the maximum service load. The maximum deflection recorded is 0.095” at the peak service load value of 16.6 Kips, after 5,000,000 cycles of loading was logged.

Fatigue Specimen #2 showed no evidence of degradation in the stiffness of the grid deck; hence it appears that no debonding of the concrete occurred in this case. The stresses in the main bars remained constant throughout the entire 2,000,000 cycles of loading. The maximum stress calculated in Main Bar #3 is 6.00 Ksi, which is well under the endurance limit for AASHTO Fatigue Category “C”. The deflections of the grid deck were also under the maximum deflection limit of L/1000 at the maximum service load at 2,000,000 cycles. The largest deflection value recorded is 0.071”, which occurred at the peak service load of 26 Kips, after 2,000,000 cycles was logged.

The ultimate strength specimens showed, on average, a reduction of 10% in the peak load between the “fresh” decks and the grid decks which had been cycled for fatigue. Ultimate Strength Specimens #2, #3, and #4 had the same failure modes (asymmetrical with a collapse mechanism forming in the south span), as well as the peak load values being within 10% of each other. As for Ultimate Strength Specimen #1, the failure mode was symmetrical, and the failure was of the concrete debonding, very suddenly, from the steel of the grid work. The peak load was much higher than any of the other three ultimate strength tests. Despite the very large wheel loads the steel in Ultimate Strength Specimen #1 did not yield.

Although the tests conducted in this work endeavored to be as representative of the field conditions as possible there are several differences between the lab testing and typical field installations. These deviations are conservative in nature; therefore the actual field performance of the larger span concrete filled grid decks should be better than what was observed during the laboratory testing:

1. The laboratory panels are only 6’ wide while field installed grid panels are much wider than this. The increase in the deck width will result in more

favorable stress distribution since orthotropic plate behavior will increase with the larger widths of the field installed panels.

2. The wheel loadings for both the fatigue and the ultimate strength tests were positioned at the most critical location, i.e. the worst load case. The load was also stationary for both of the testing situations. This critical loading will exploit any damage that might occur during the fatigue testing, and make the damage worse than what would actually happen on an in-service grid deck.

3. The grid decks were not held down at the supporting members in anyway during the laboratory testing. Conversely, in field applications the grid deck would be attached to the supporting member with shear studs and a concrete haunch that is typically used to connect the deck to a supporting member. Thus the grid deck and the supporting members would act compositely, thereby producing a more favorable stress distribution; much more favorable than what was observed during the laboratory testing.

APPENDIX A

APPENDIX A

Figure A-1 Grid Deck Test Specimen
-Prior To Concrete Placement

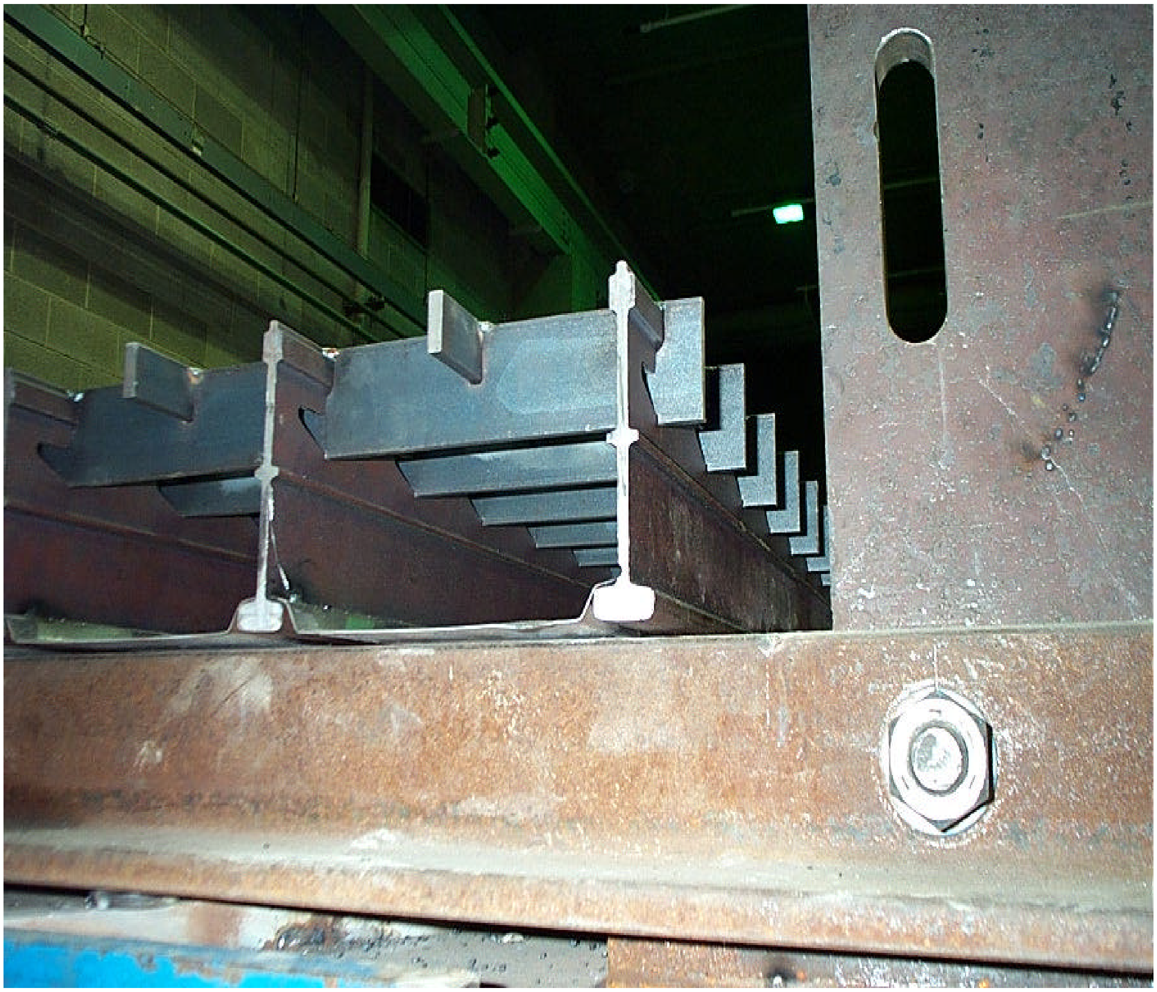

Figure A-2 Northern Roller Support

Figure A-3 Middle Roller Support

Figure A-4 Southern Roller Support

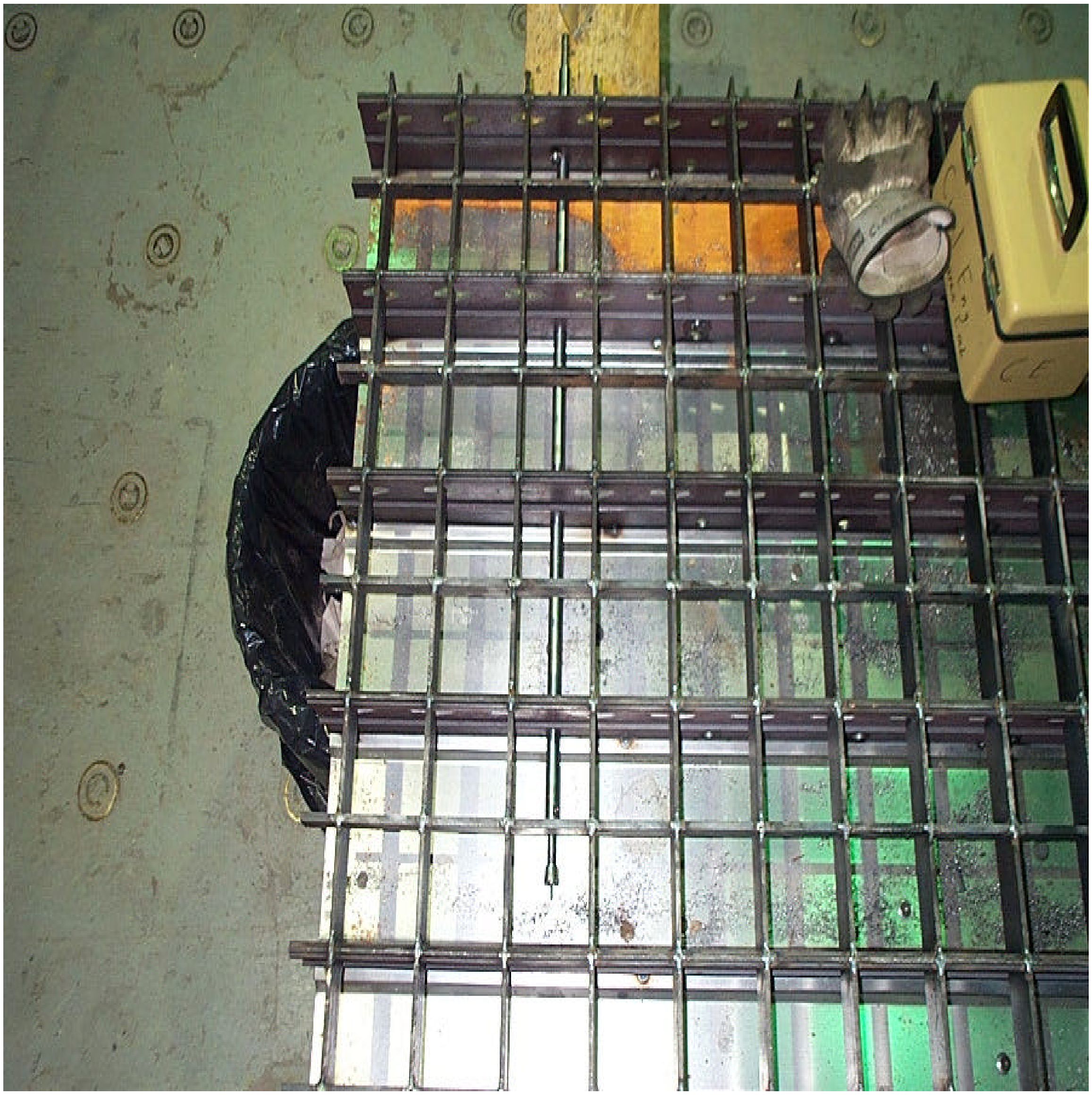

Figure A-5 Installation of Lower Cross Bars
-3' Long Drill Bit Shown

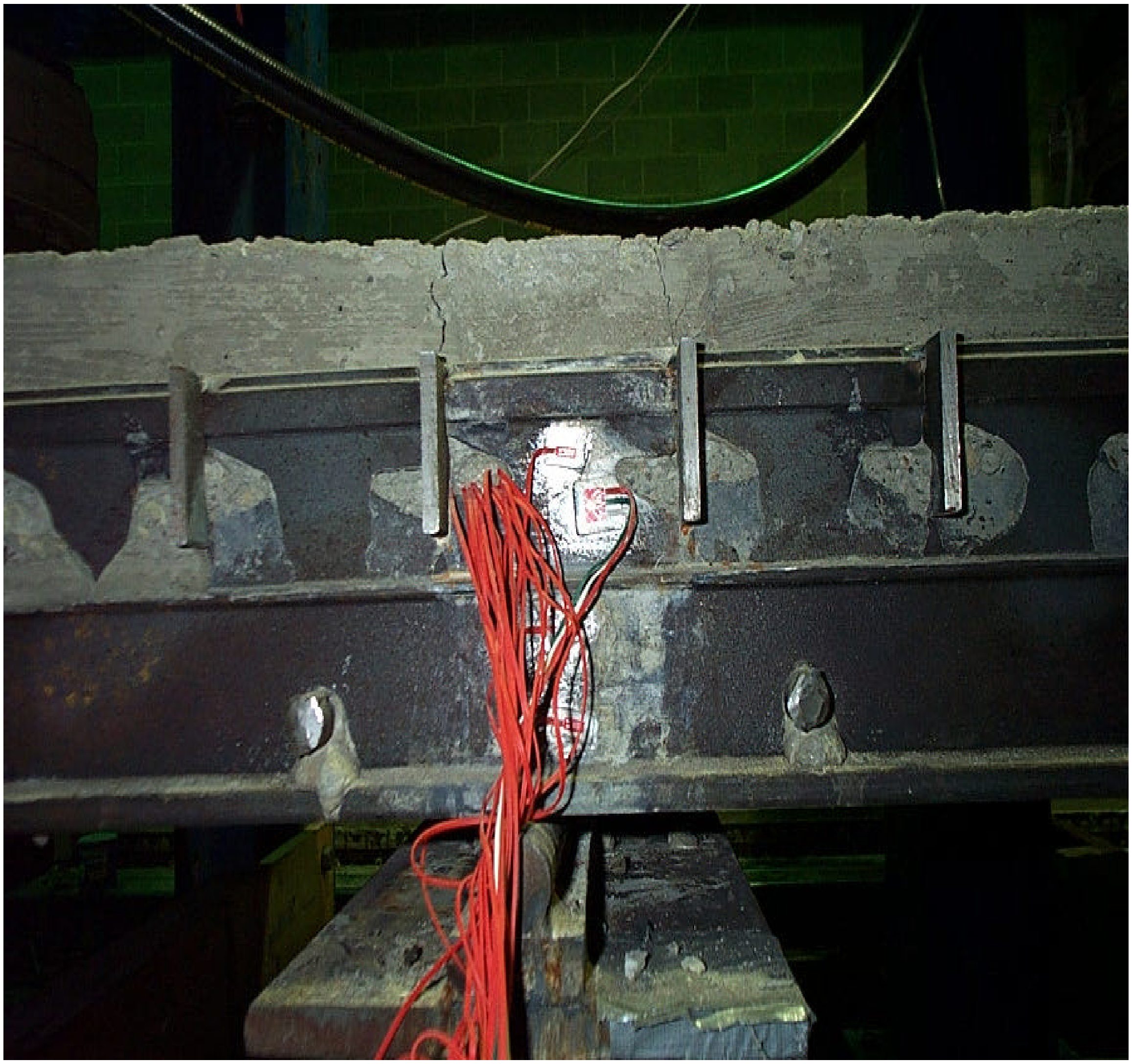

Figure A-6 Foil Strain Gauges
-Located At Middle Support

Figure A-7 Formwork
-Fatigue Specimen #1 Shown

Figure A-8 Formwork of Remaining Grid Deck Specimens

Figure A-9 Typical Lifting Point

Figure A-10 First Concrete Placement
-Fatigue Specimen #1 During Finishing

Figure A-11 Concrete Placement of Remaining Grid Deck Specimens
-Ultimate Strength Specimen #2 Shown

Figure A-12 Concrete Placement of Remaining Grid Deck Specimens
-Fatigue Specimen #2 Shown

Figure A-13 Concrete Placement of Remaining Grid Deck Specimens
-Ultimate Strength Specimens #1& #2 Shown

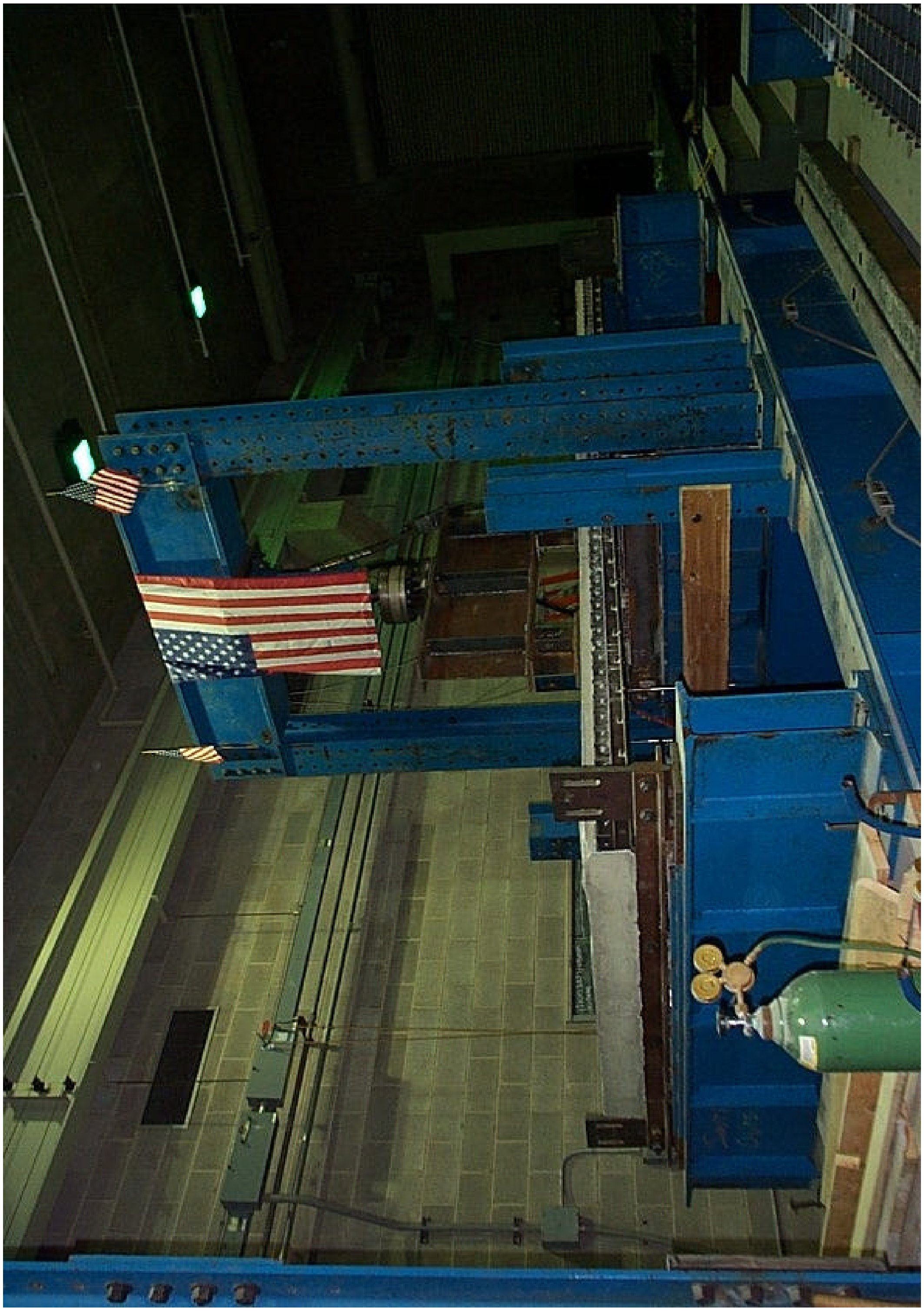

Figure A-14 Fatigue Specimen #1
-Testing Phase

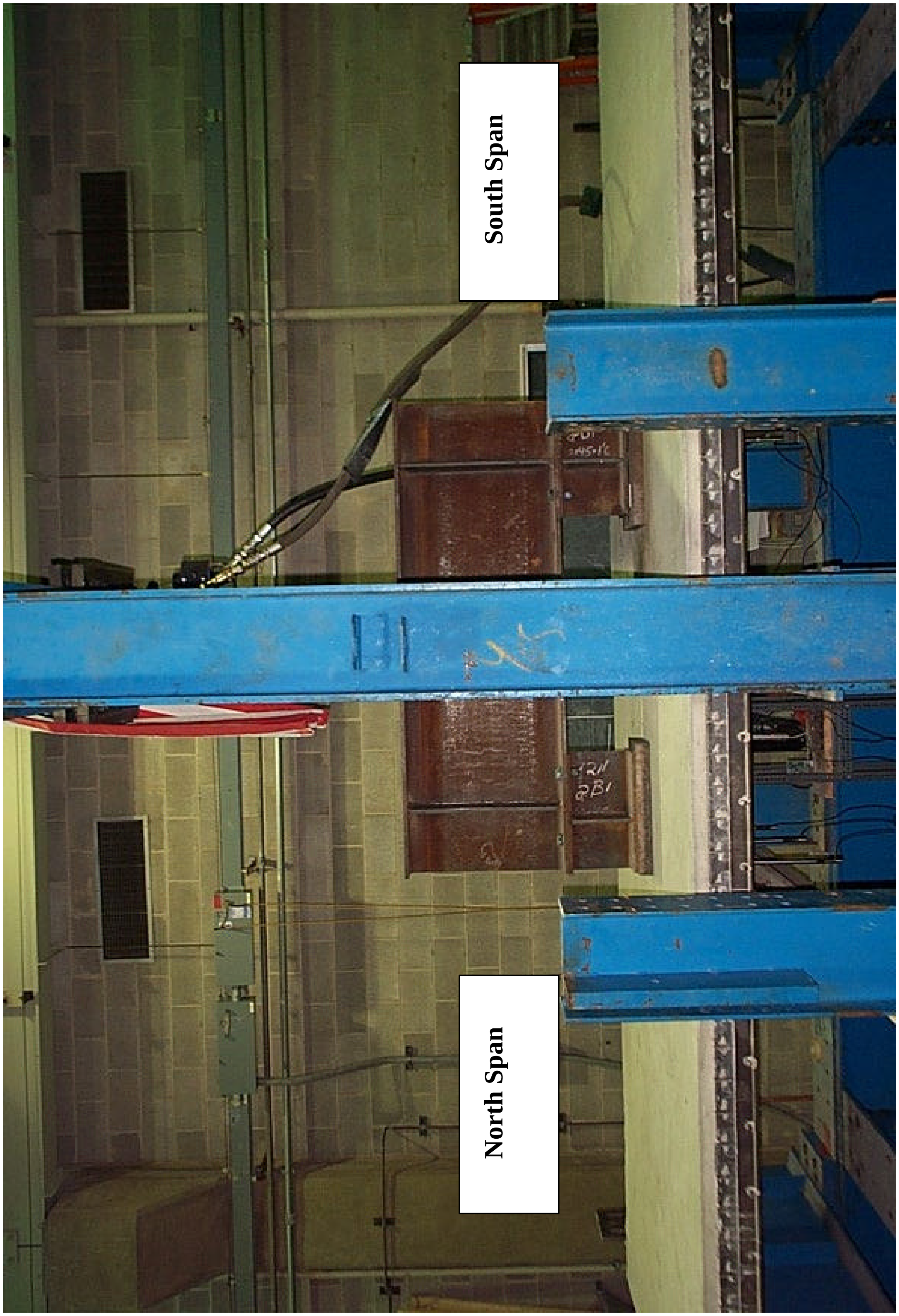

Figure A-15 Fatigue Test Specimen Span Breakdown

Figure A-16   Ultimate Strength Test Specimen Span Breakdown

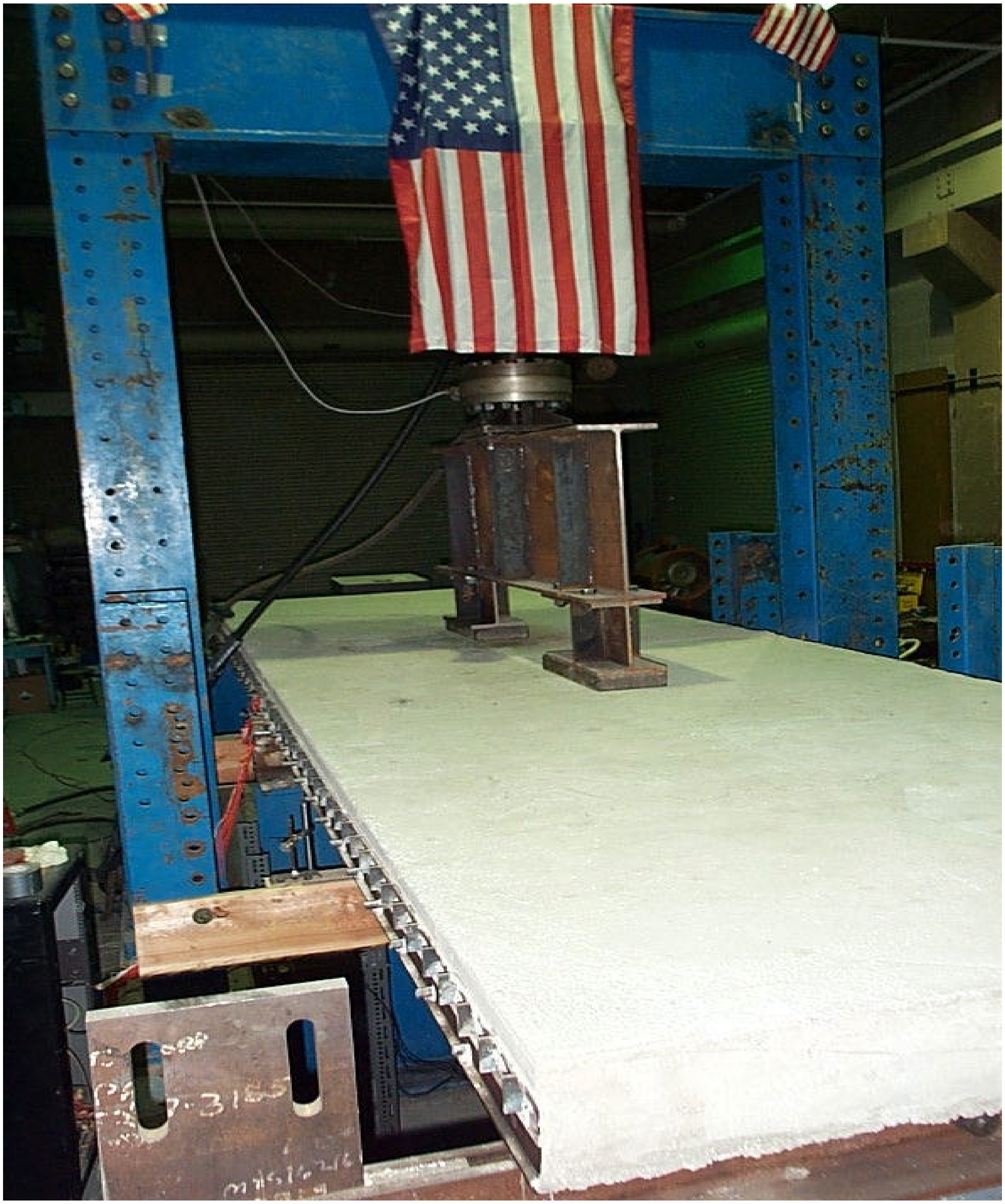

Figure A-17 Fatigue Specimen #1
-Spreader Beam and Actuator Set-Up

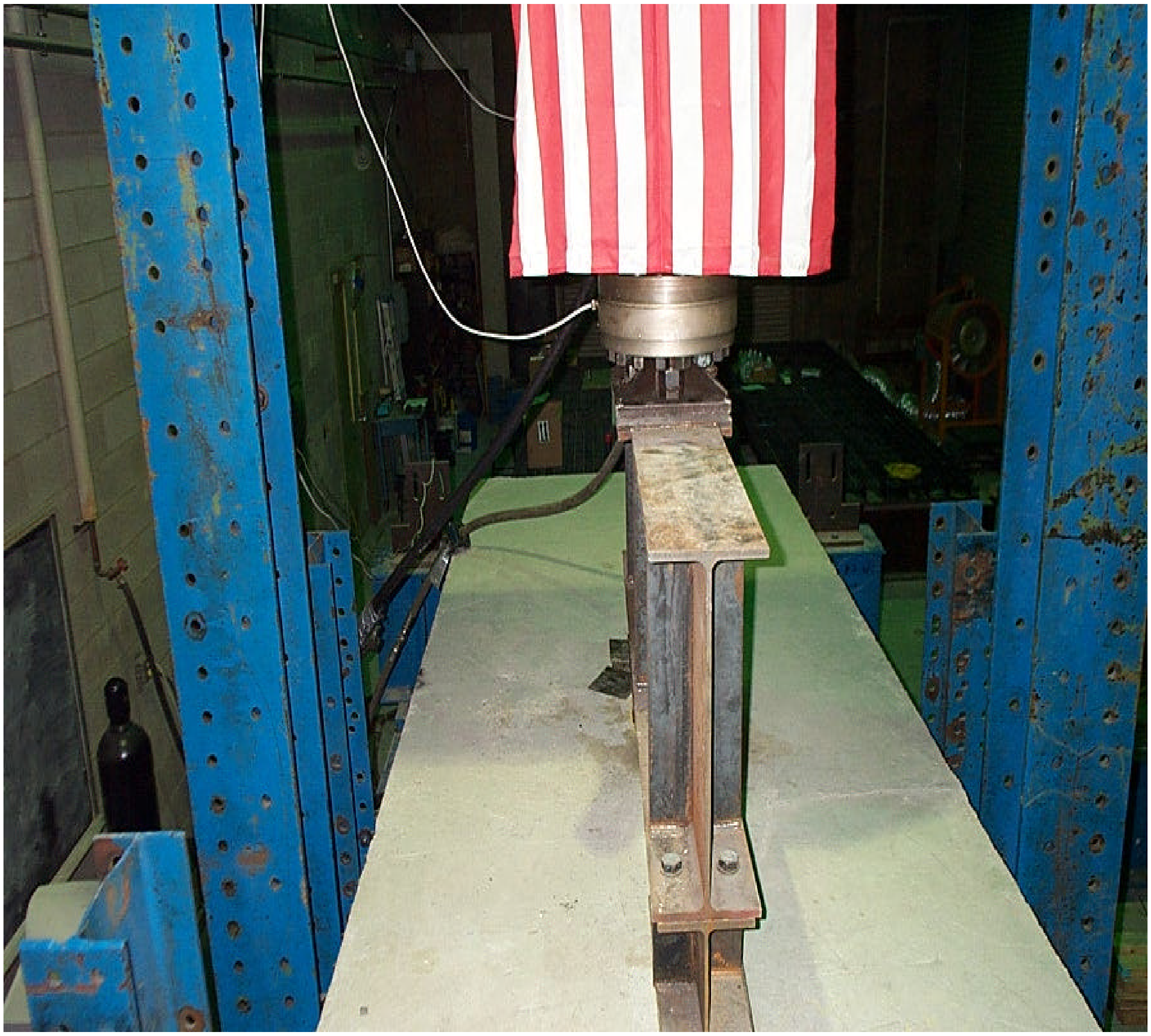

Figure A-18 Close Up of Spreader Beam and Load Cell

Figure A-19 Close-Up of Loading System
-Spreader Beam and 2"x8"x20" Steel Plates

Figure A-20 MTS 458 Controller, Microprofiler, and Oscilloscope

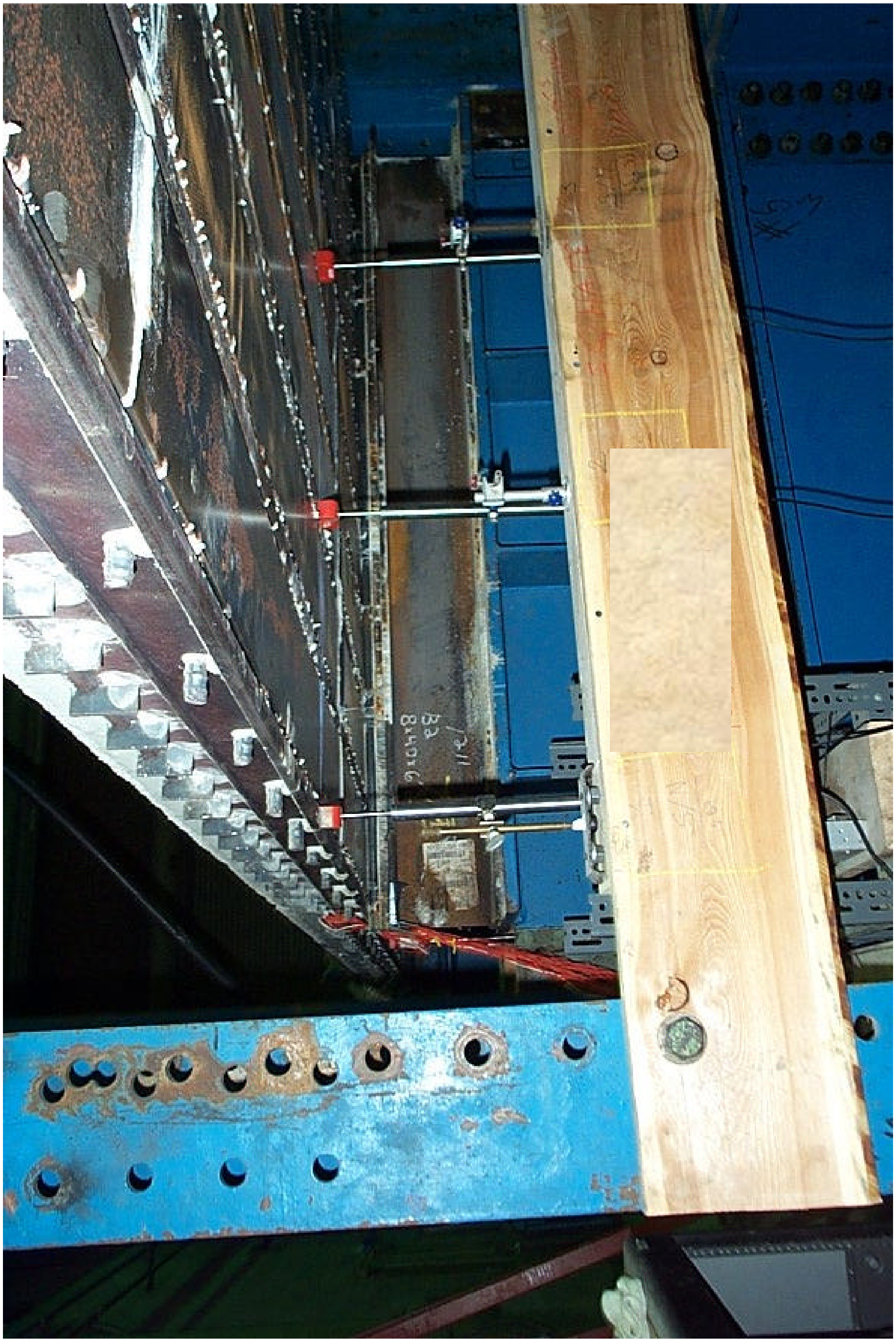

Figure A-21 Close-Up View of DCDTs
-North Span

Figure A-22 Data Acquisition System
-Computer and System 5000

Figure A-23 Ultimate Strength Test Set-Up
-Ultimate Strength Specimen #1 Shown

Figure A-24 Ultimate Strength Test Set-Up
-Ultimate Strength Specimen #1 Shown

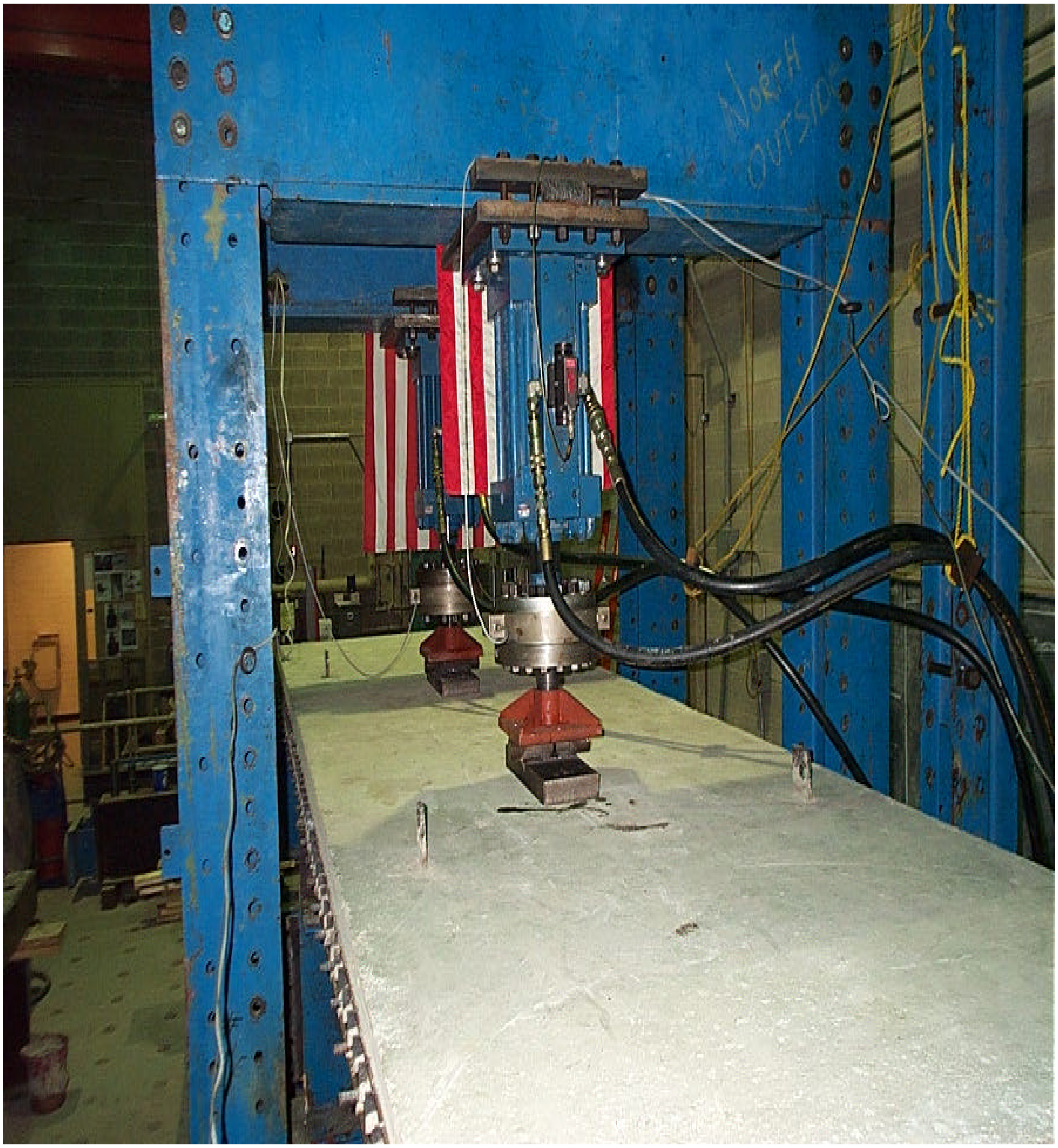

Figure A-25 Ultimate Strength Test
-Loading System Set-Up

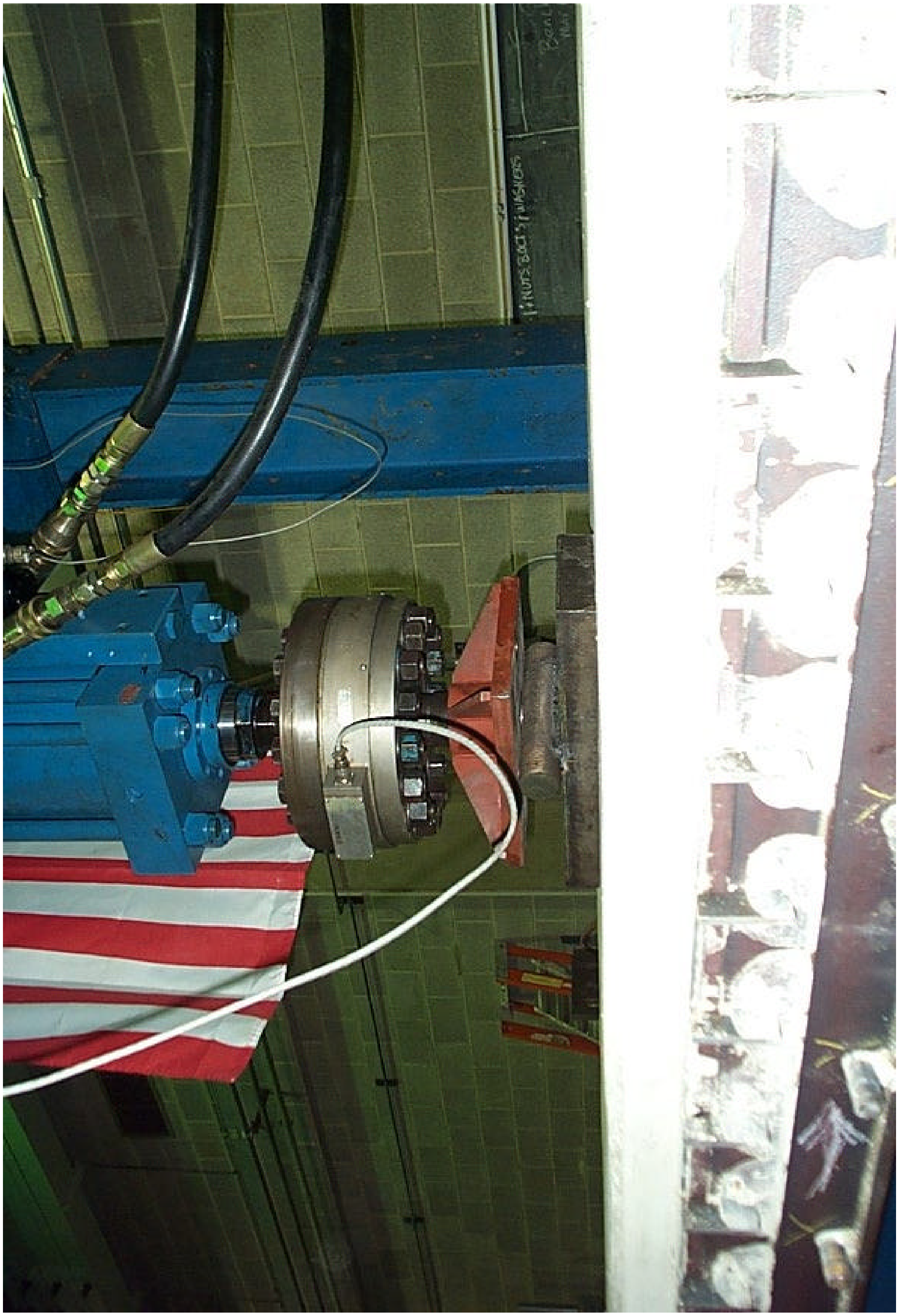

Figure A-26 Ultimate Strength Test Set-Up
-Close-Up of Loading System

Figure A-27 Ultimate Strength Test
-Negative Moment Cracks at Middle Support

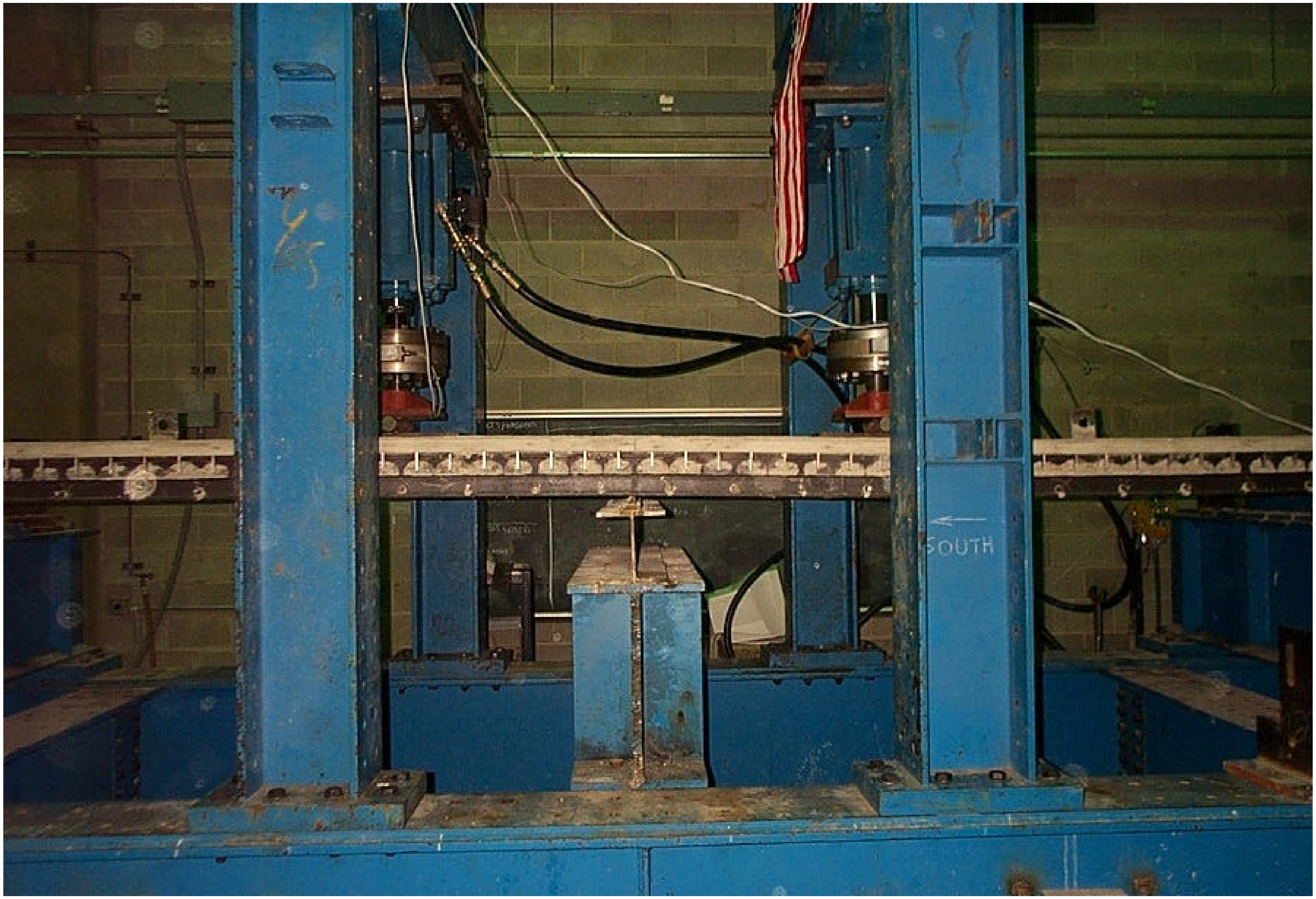

Figure A-28 Ultimate Strength Test
-During Testing (Note Asymmetrical Deflection)

Figure A-29 Ultimate Strength Test
-During Testing (Note Deck Deflection)

Figure A-30 Ultimate Strength Test #4 After Testing
-8"x20" Plate Embedded in Concrete

APPENDIX B

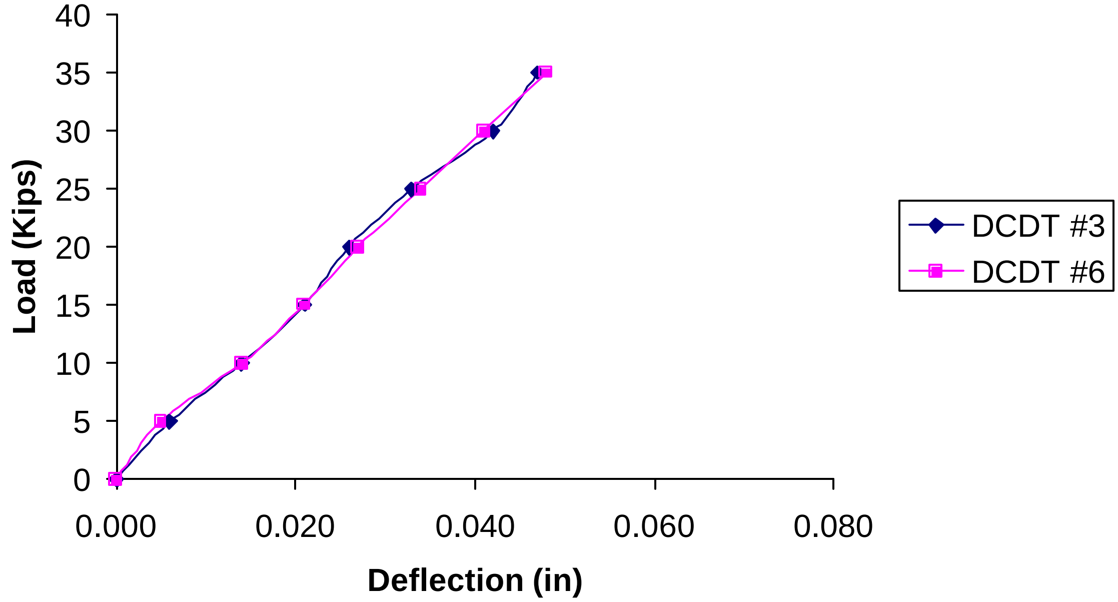

Figure B-1 Fatigue Specimen #1 Main Bar #1-Benchmark

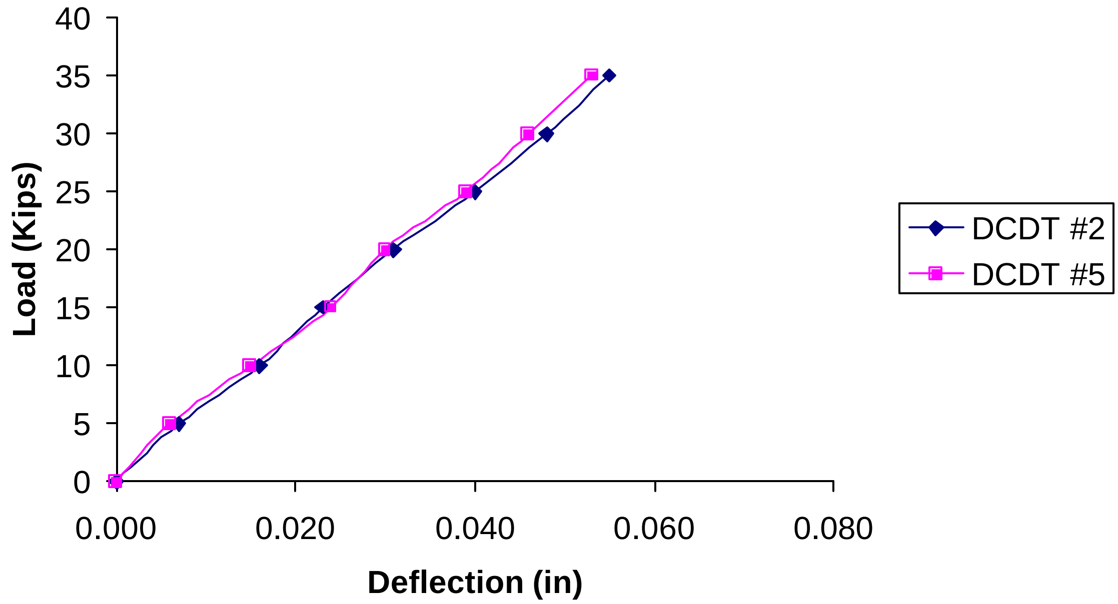

Figure B-2 Fatigue Specimen #1 Main Bar #2-Benchmark

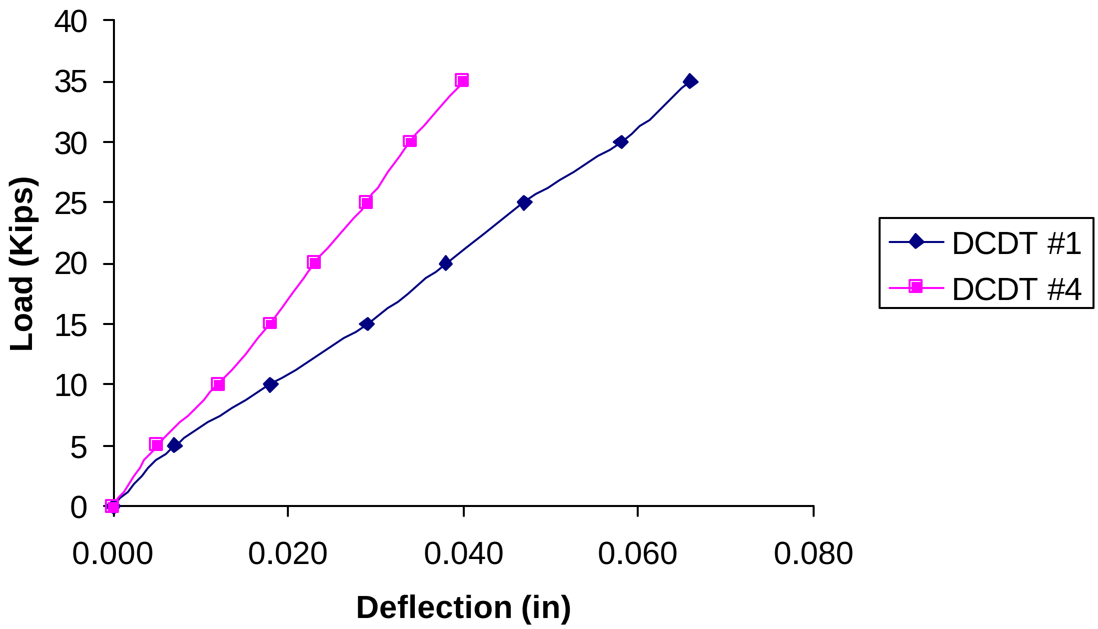

Figure B-3 Fatigue Specimen #1 Main Bar #3-Benchmark

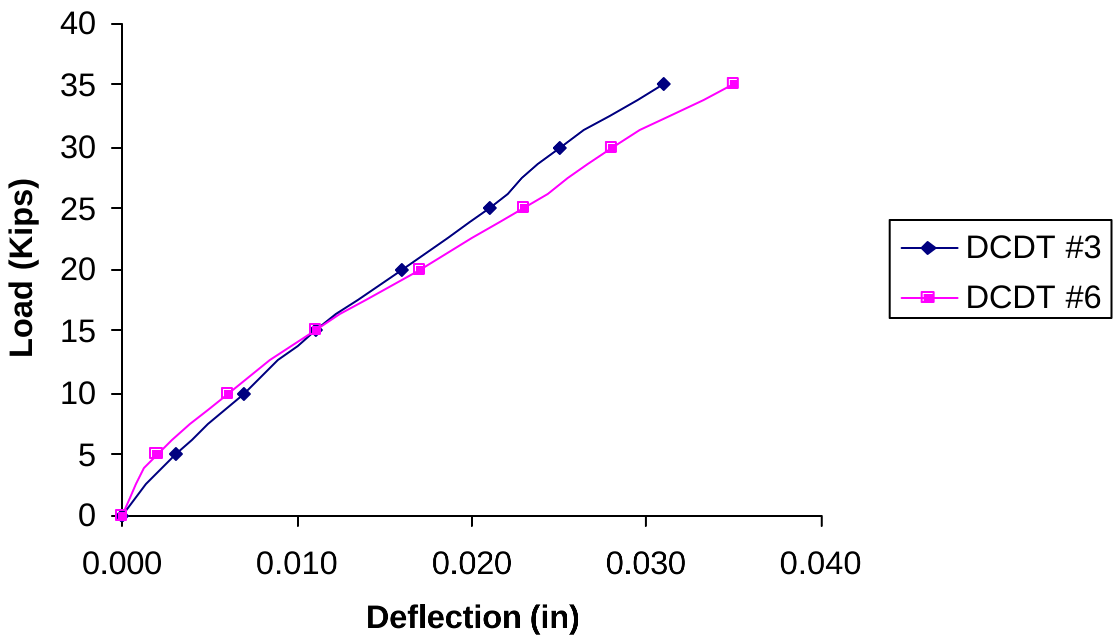

Figure B-4 Fatigue Specimen #1 Main Bar #1-150K Cycles

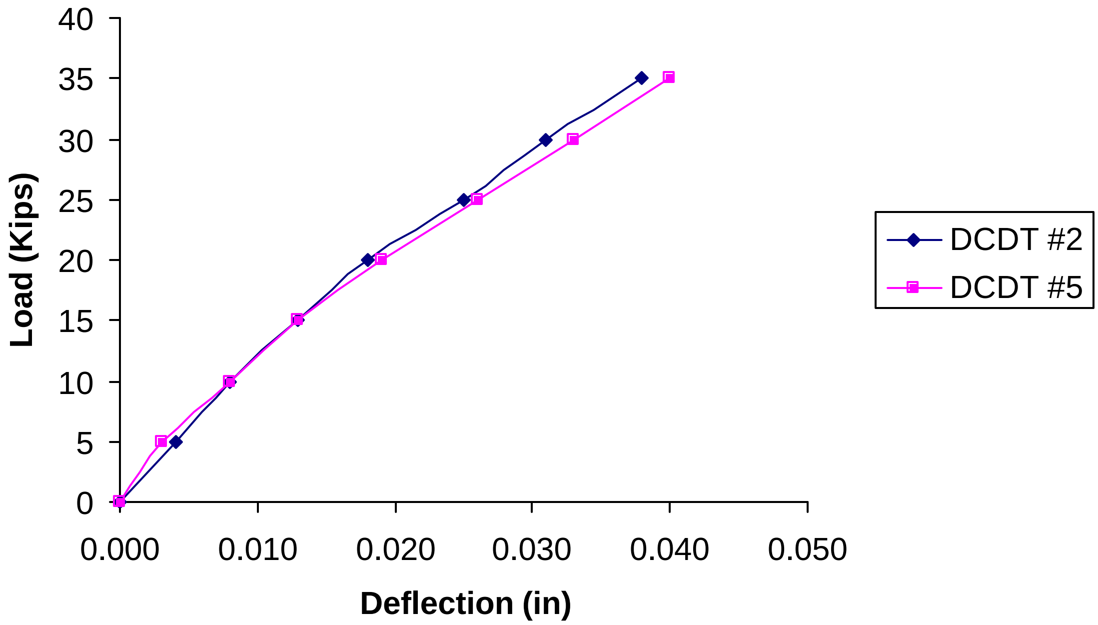

Figure B-5 Fatigue Specimen #1 Main Bar #2-150K Cycles

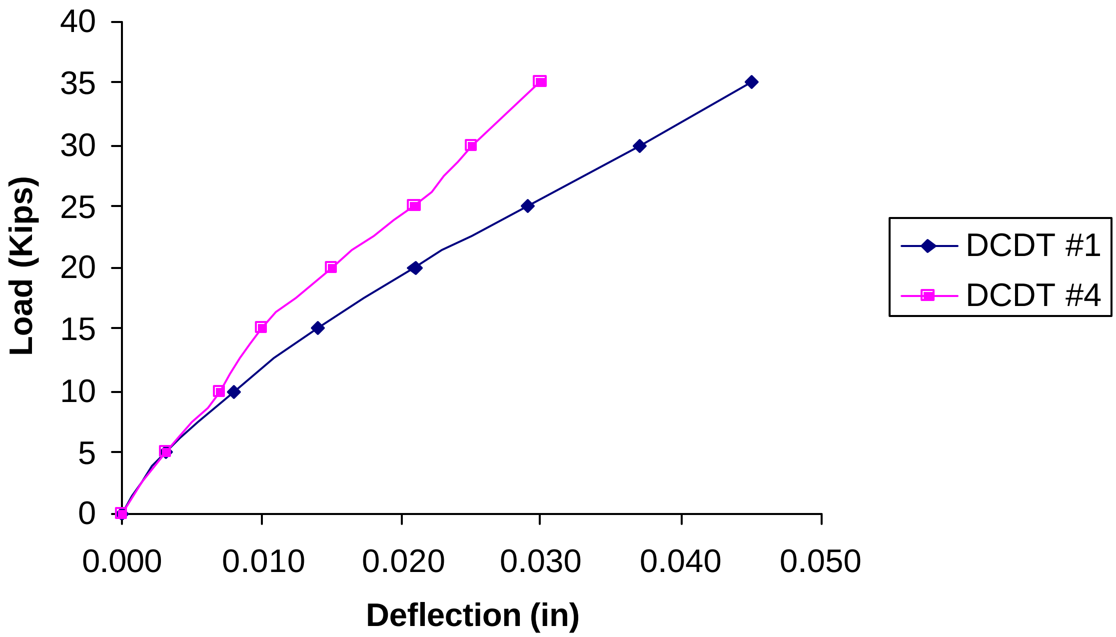

Figure B-6 Fatigue Specimen #1 Main Bar #3-150K Cycles

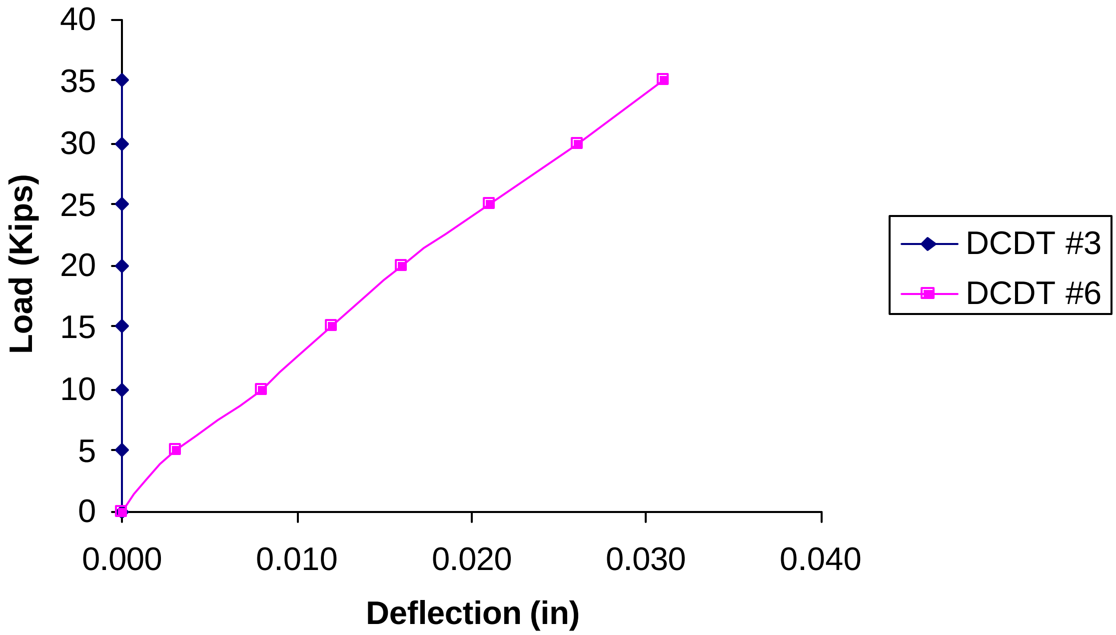

Figure B-7 Fatigue Specimen #1 Main Bar #1-300K Cycles

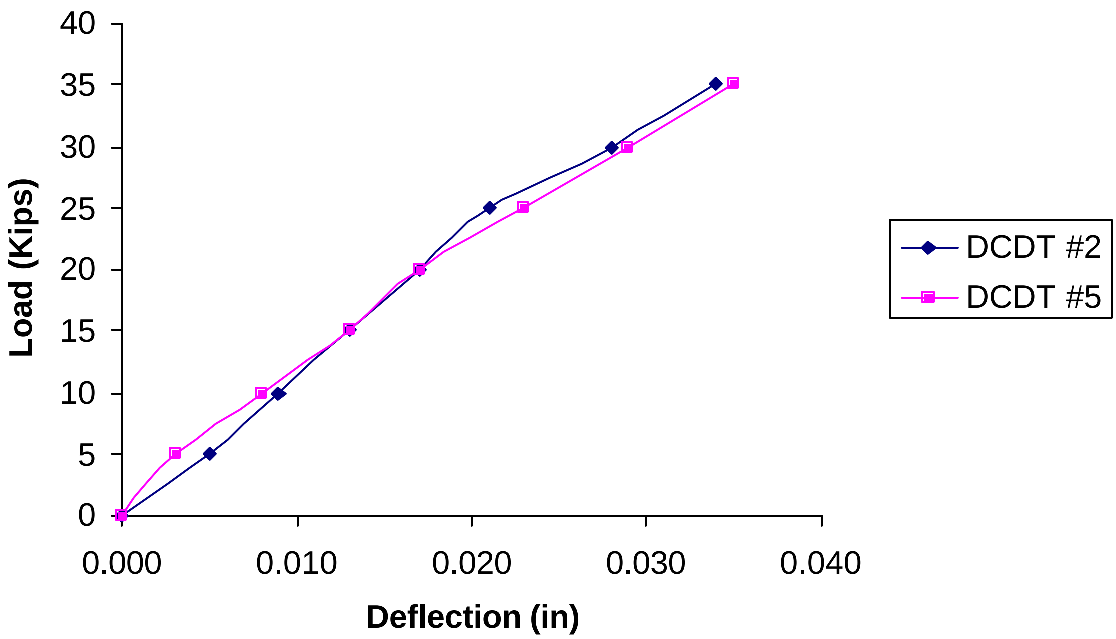

Figure B-8 Fatigue Specimen #1 Main Bar #2-300K Cycles

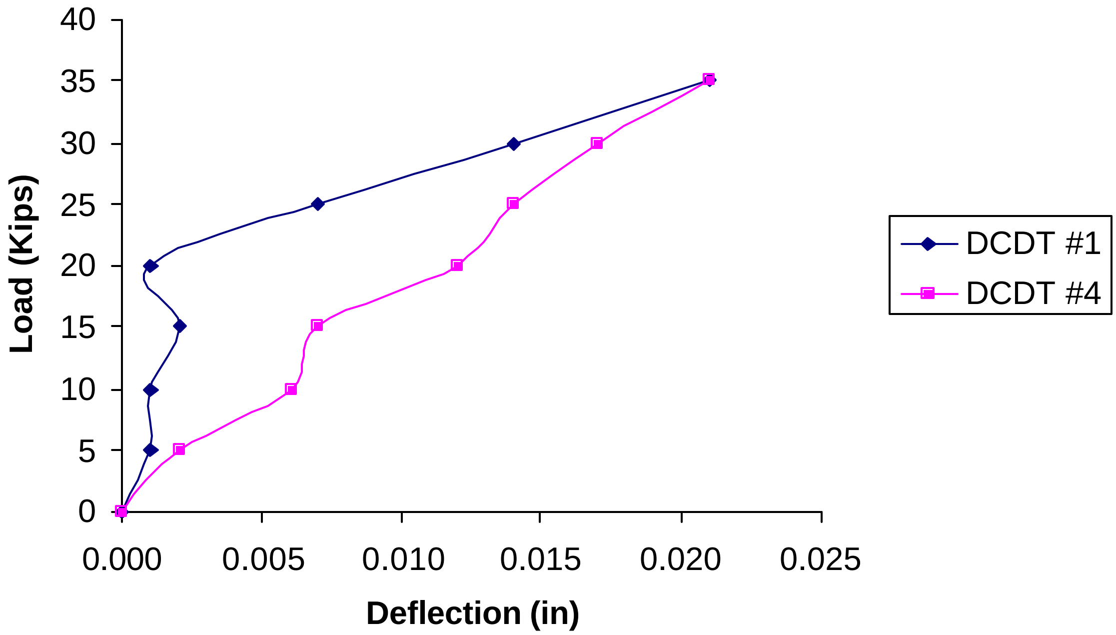

Figure B-9 Fatigue Specimen #1 Main Bar #3-300K Cycles

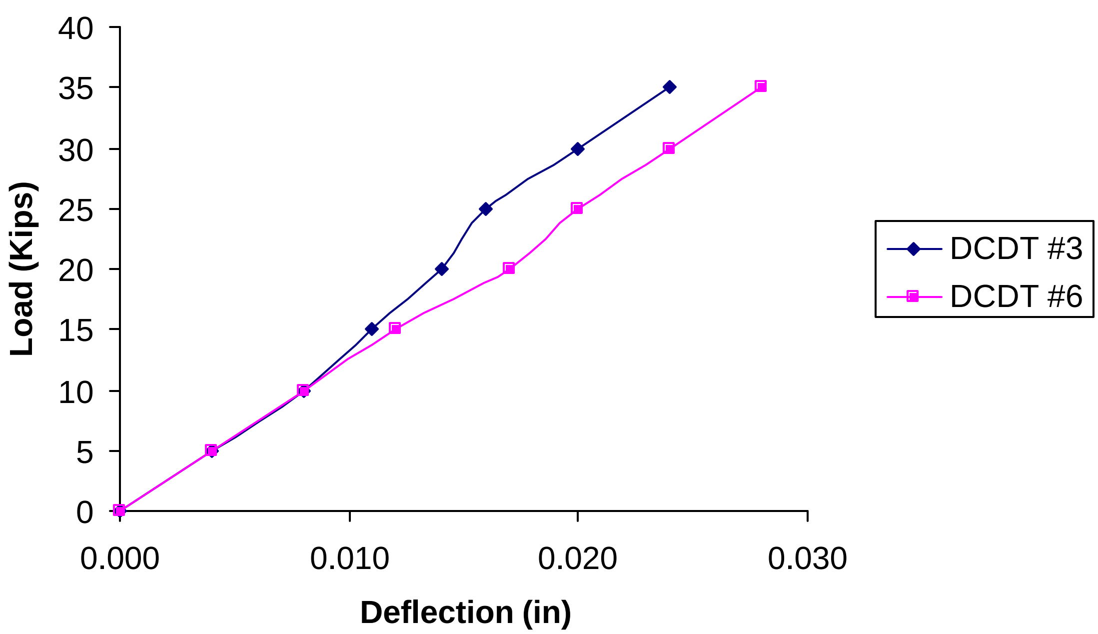

Figure B-10 Fatigue Specimen #1 Main Bar #1-450K Cycles

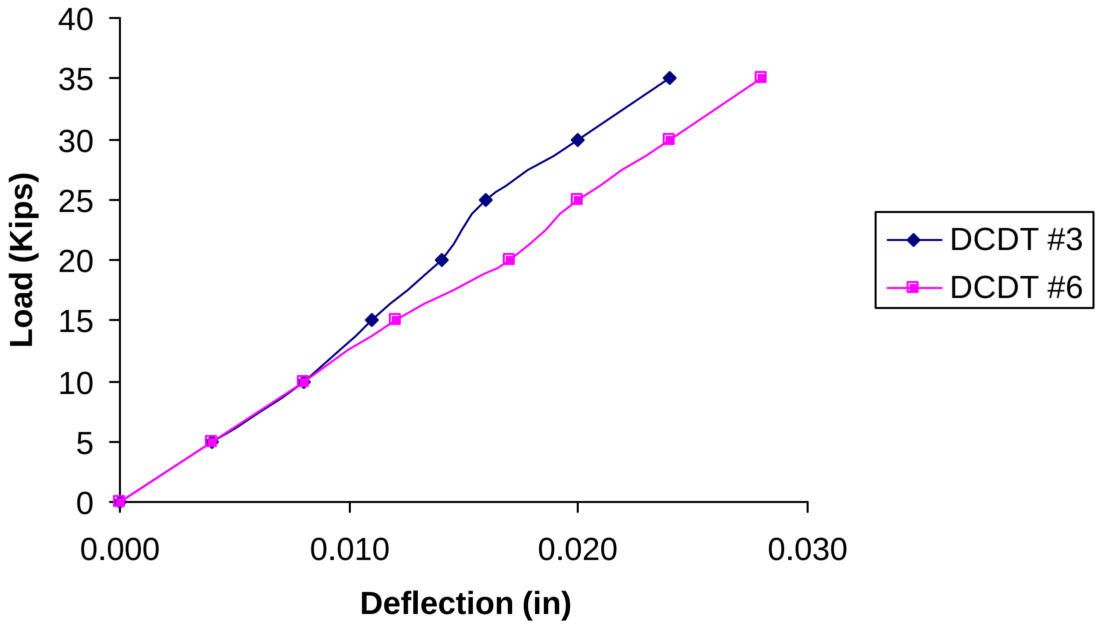

Figure B-11 Fatigue Specimen #1 Main Bar #2-450K Cycles

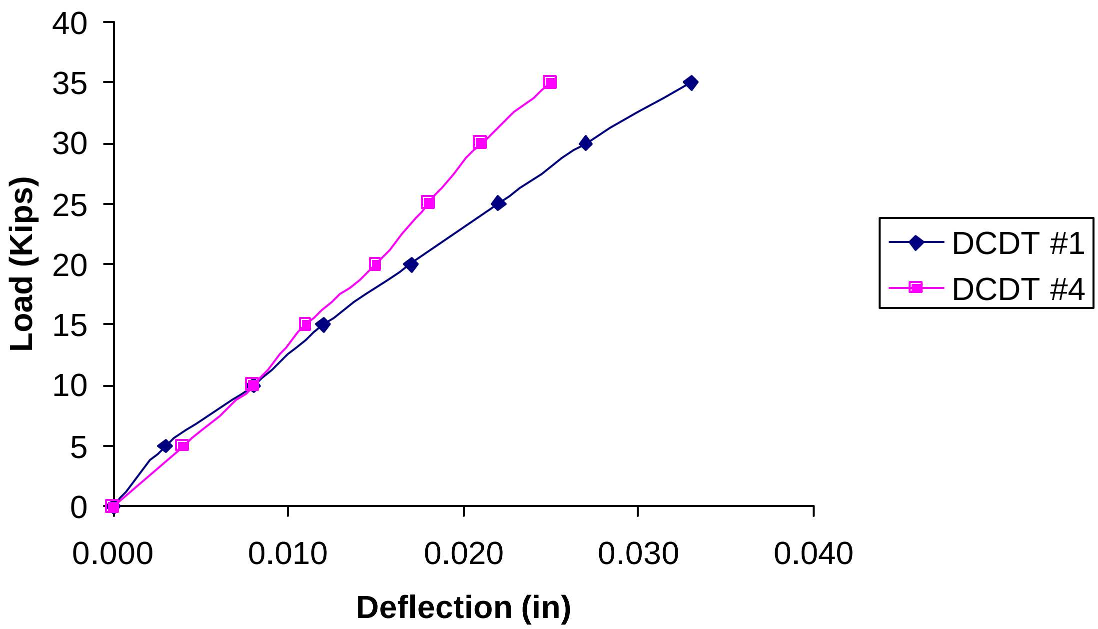

Figure B-12 Fatigue Specimen #1 Main Bar #3-450K Cycles

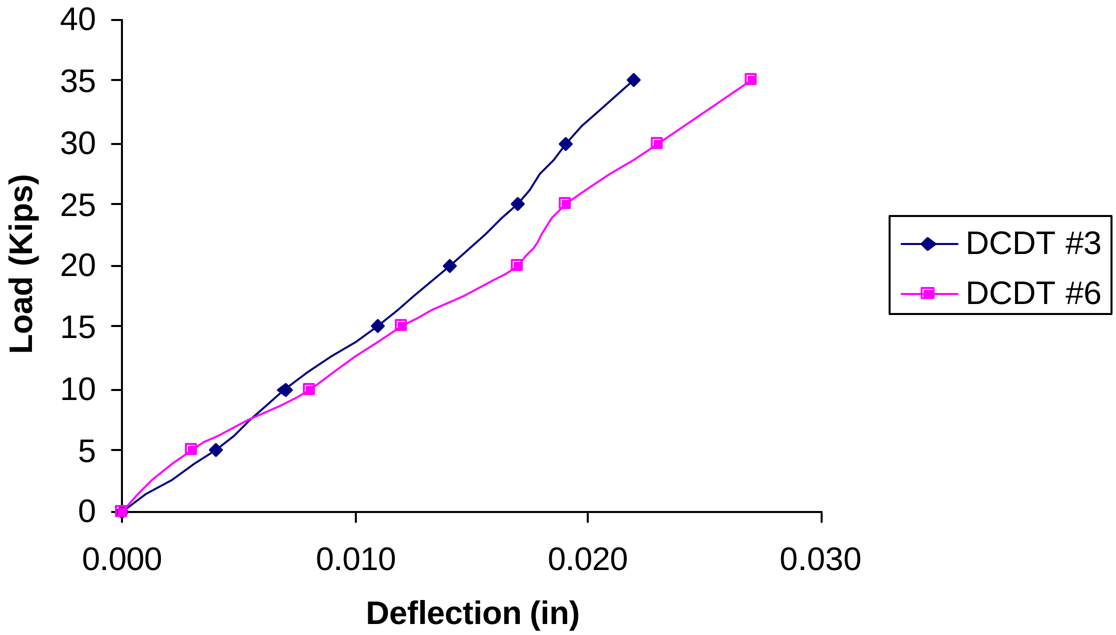

Figure B-13 Fatigue Specimen #1 Main Bar #1-600K Cycles

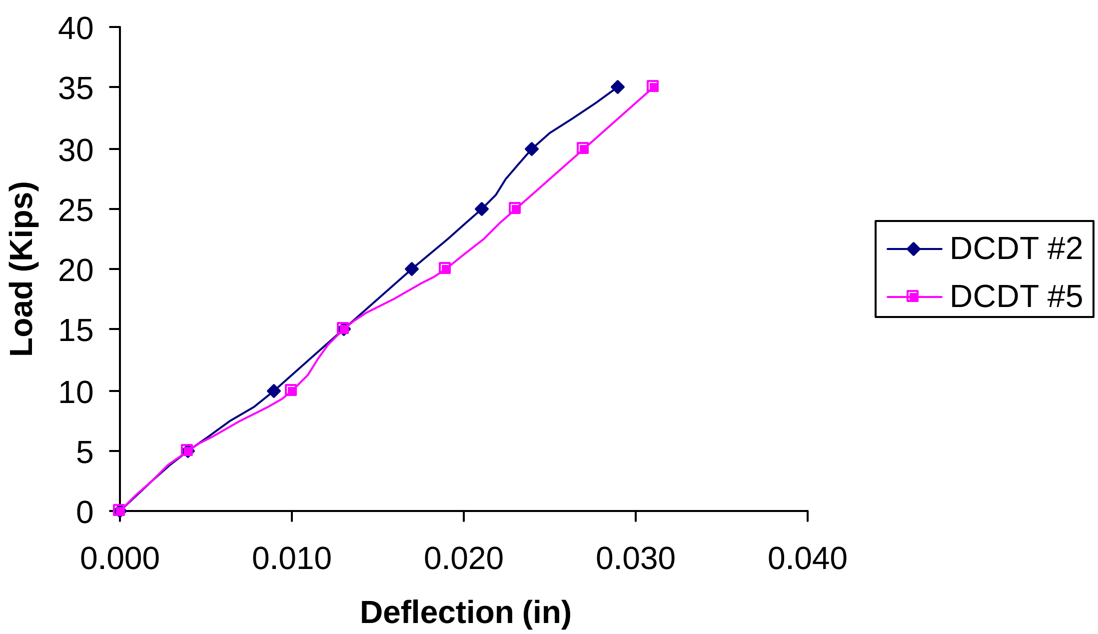

Figure B-14 Fatigue Specimen #1 Main Bar #2-600K Cycles

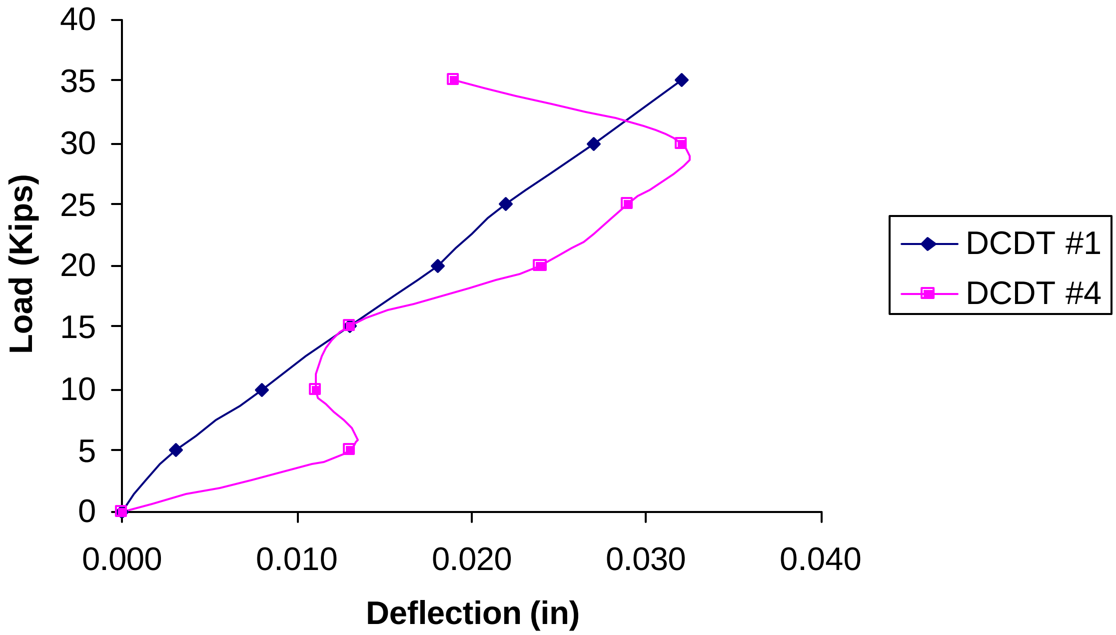

Figure B-15 Fatigue Specimen #1 Main Bar #3-600K Cycles

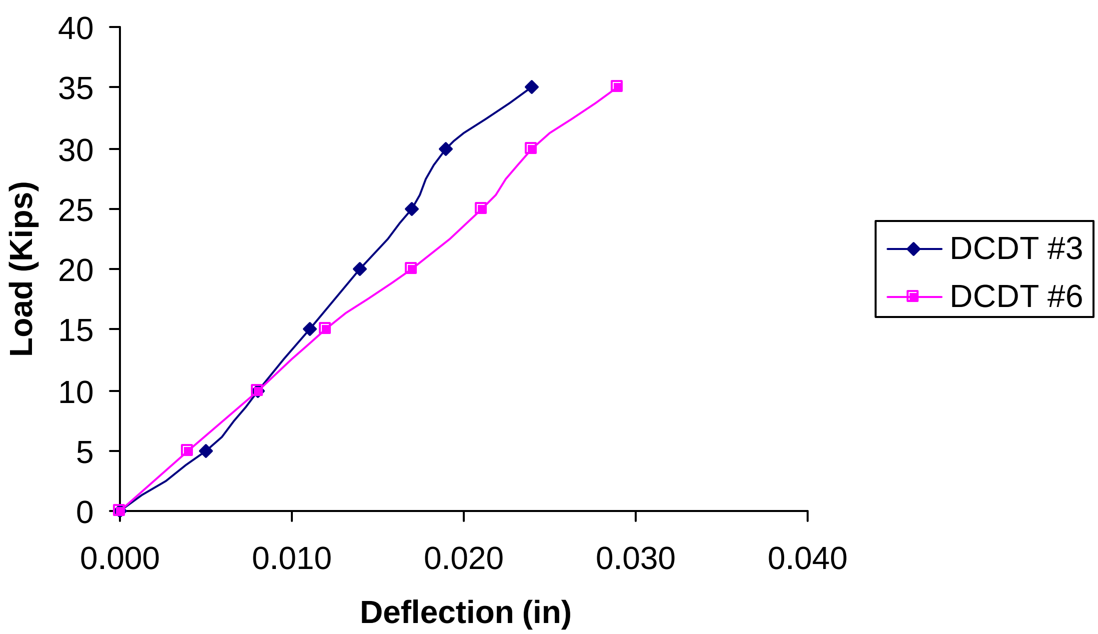

Figure B-16 Fatigue Specimen #1 Main Bar #1-750K Cycles

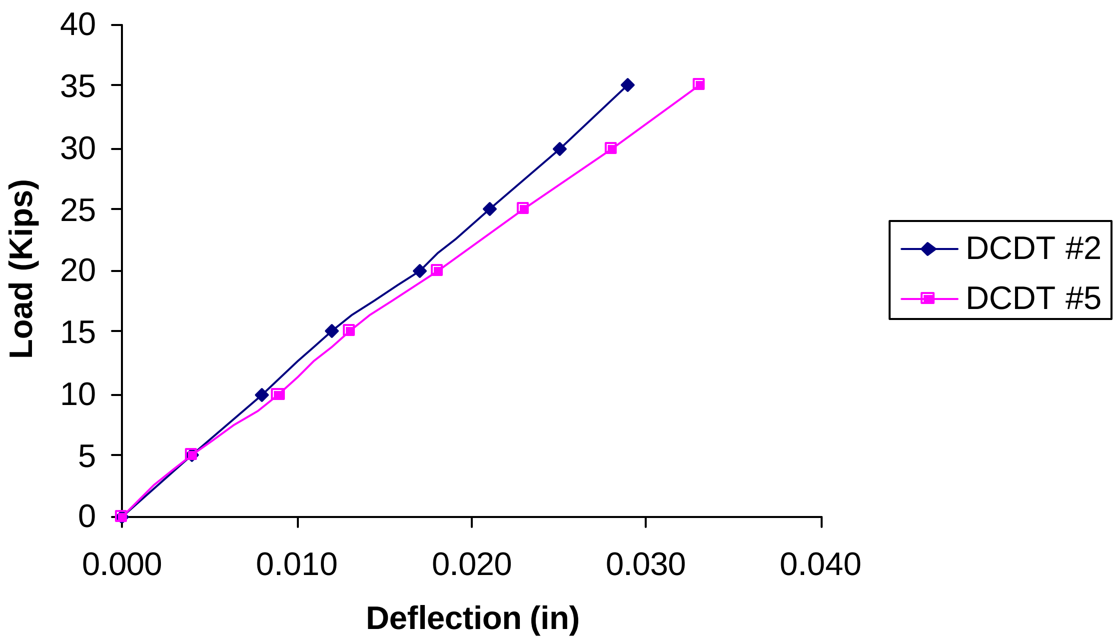

Figure B-17 Fatigue Specimen #1 Main Bar #2-750K Cycles

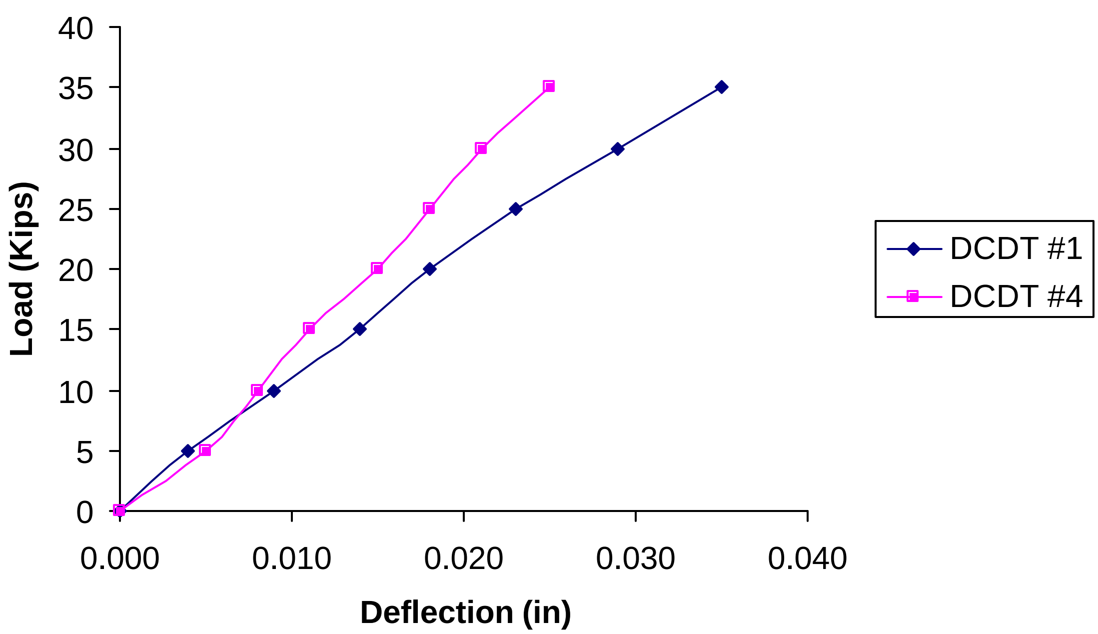

Figure B-18 Fatigue Specimen #1 Main Bar #3-750K Cycles

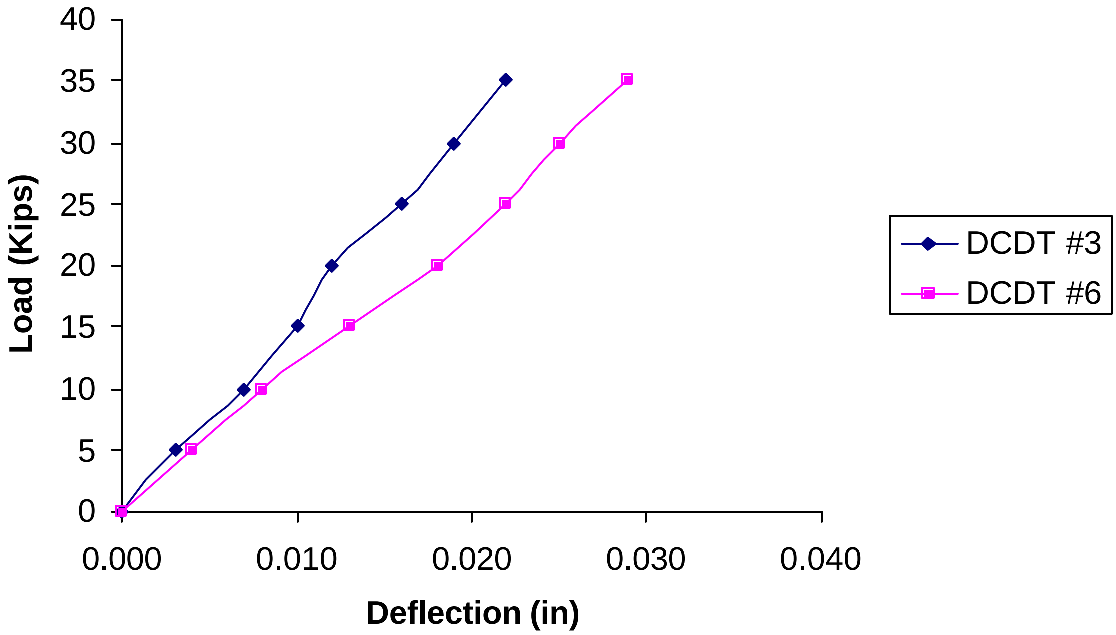

Figure B-19 Fatigue Specimen #1 Main Bar #1-900K Cycles

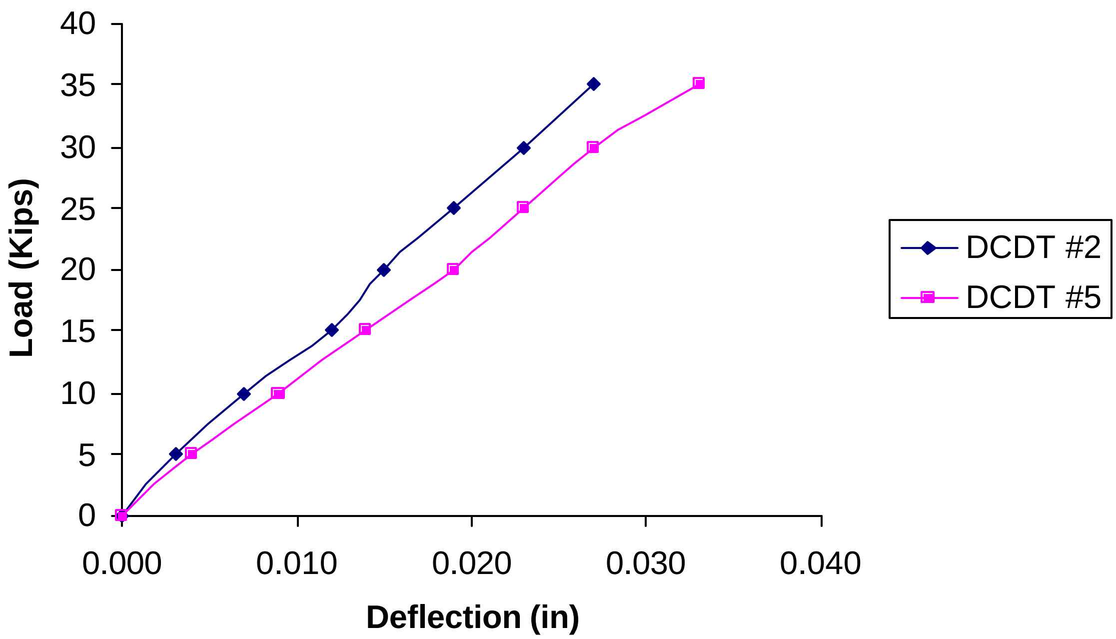

Figure B-20 Fatigue Specimen #1 Main Bar #2-900K Cycles

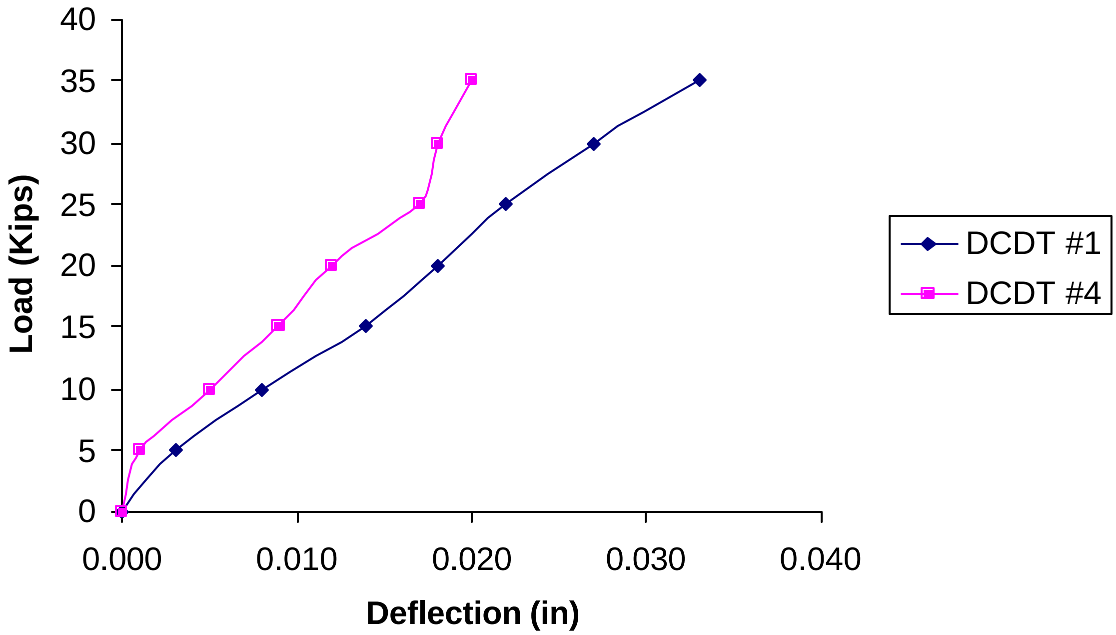

Figure B-21 Fatigue Specimen #1 Main Bar #3-900K Cycles

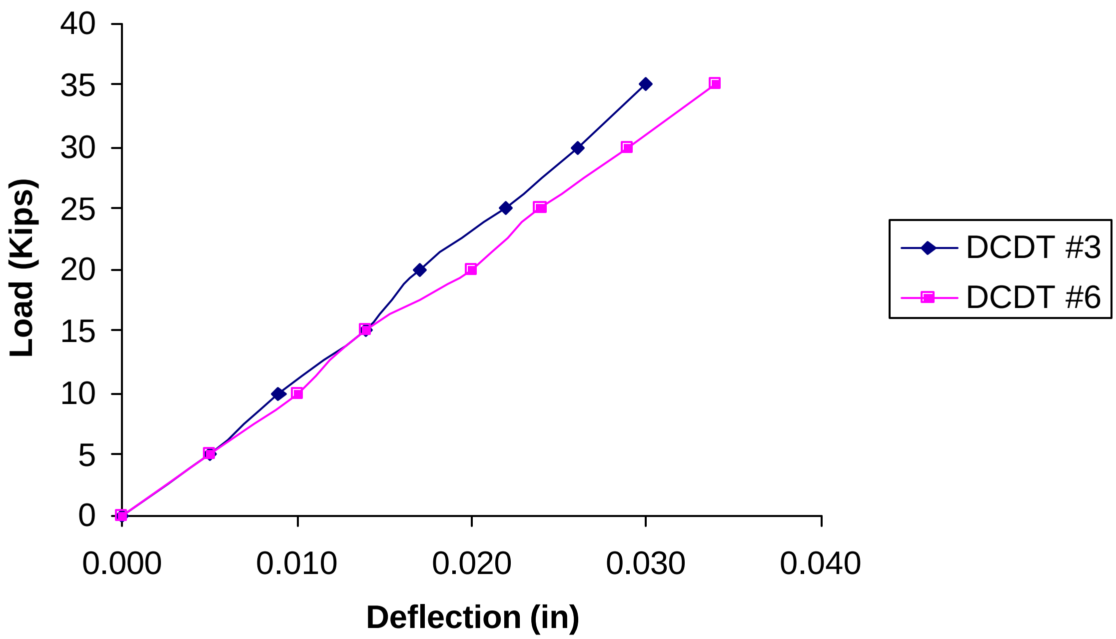

Figure B-22 Fatigue Specimen #1 Main Bar #1-1050K Cycles

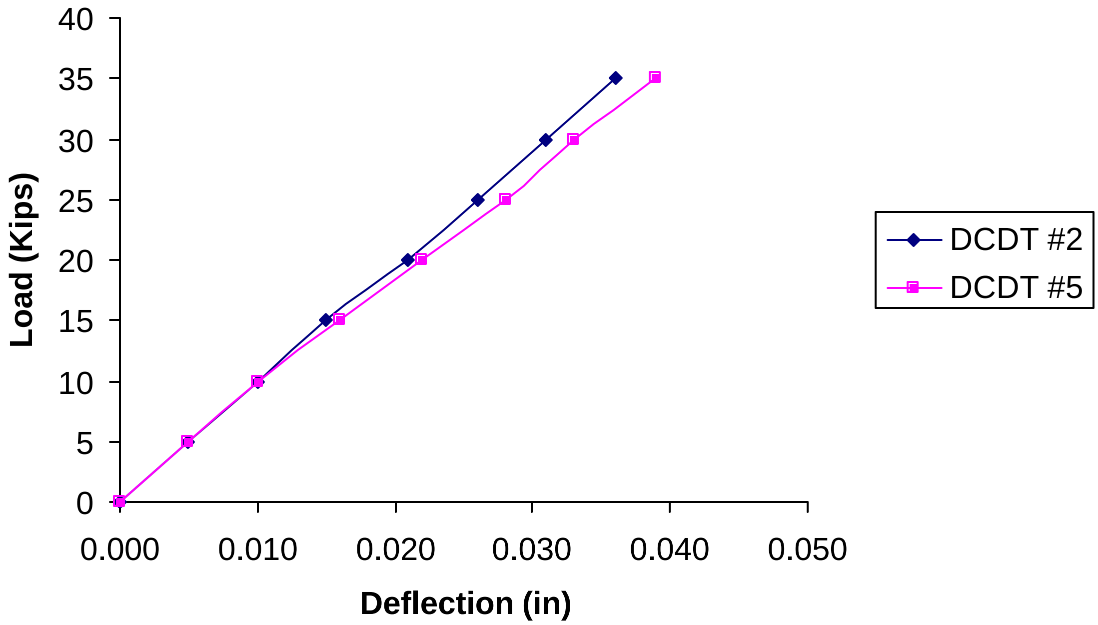

Figure B-23 Fatigue Specimen #1 Main Bar #2-1050K Cycles

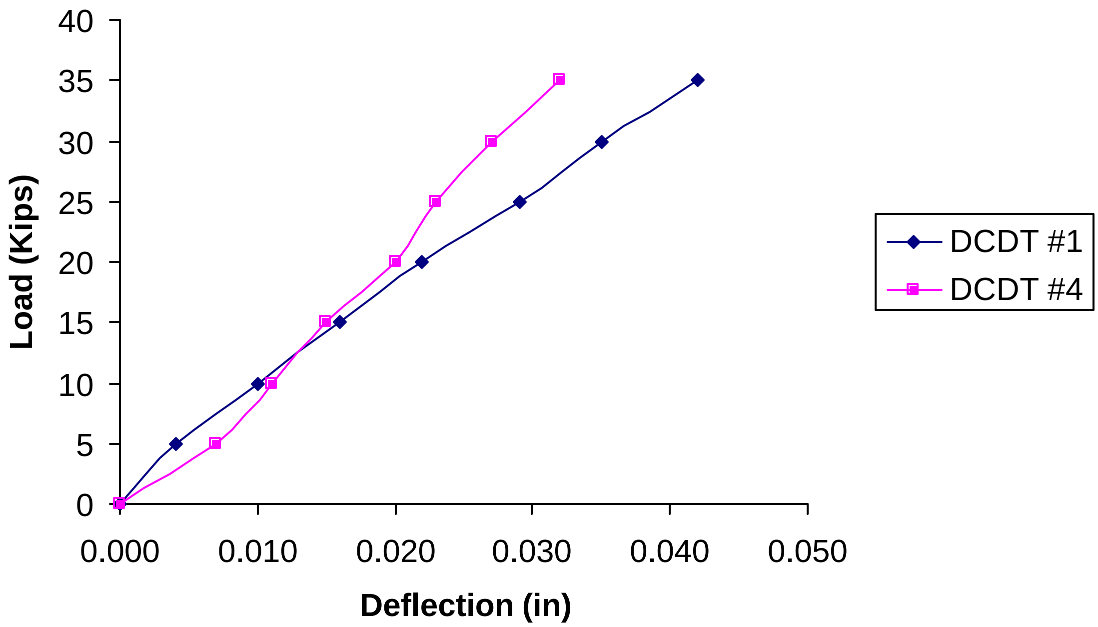

Figure B-24 Fatigue Specimen #1 Main Bar #3-1050K Cycles

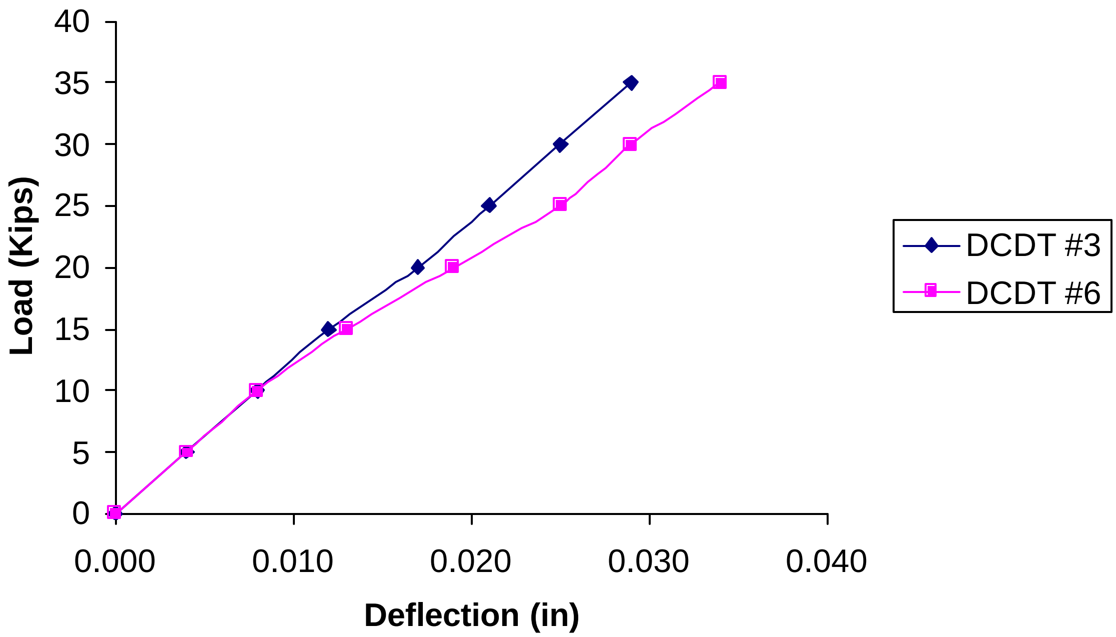

Figure B-25 Fatigue Specimen #1 Main Bar #1-1200K Cycles

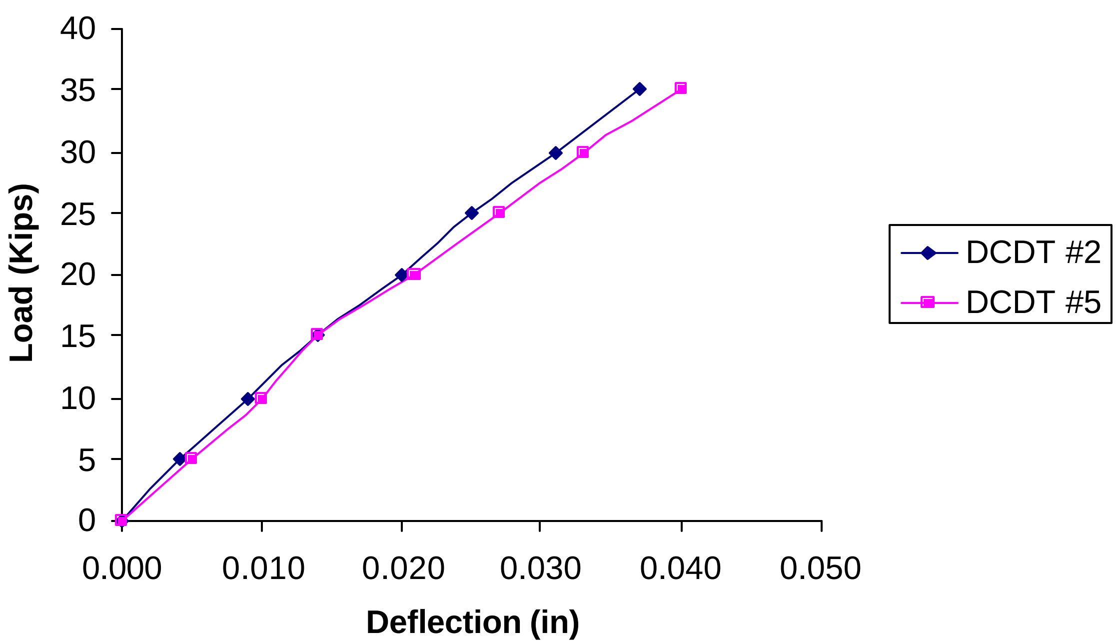

Figure B-26 Fatigue Specimen #1 Main Bar #2-1200K Cycles

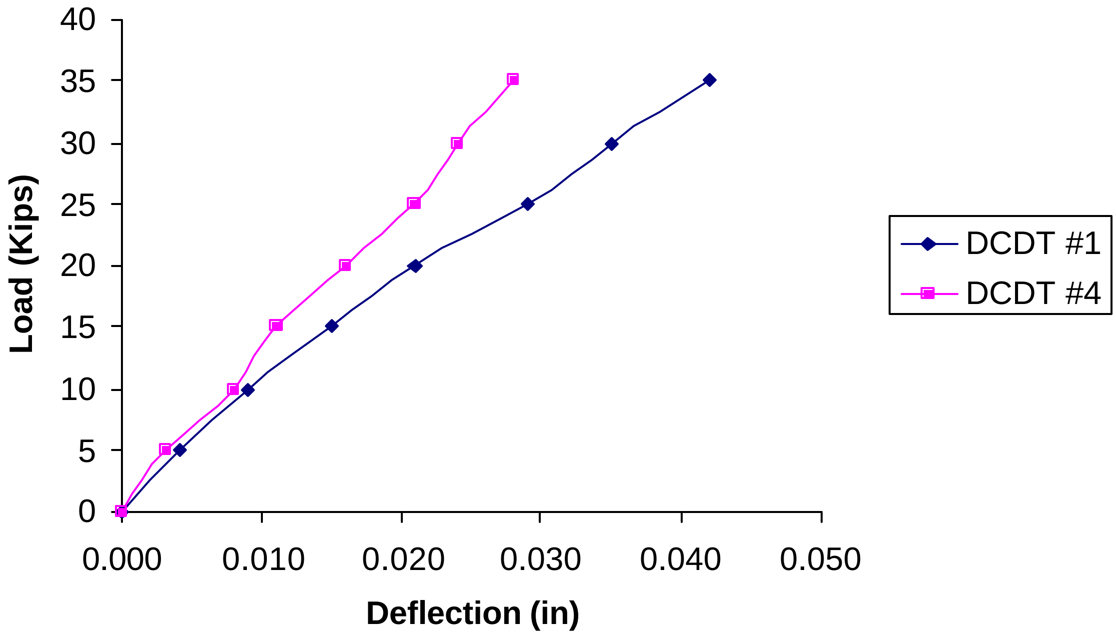

Figure B-27 Fatigue Specimen #1 Main Bar #3-1200K Cycles

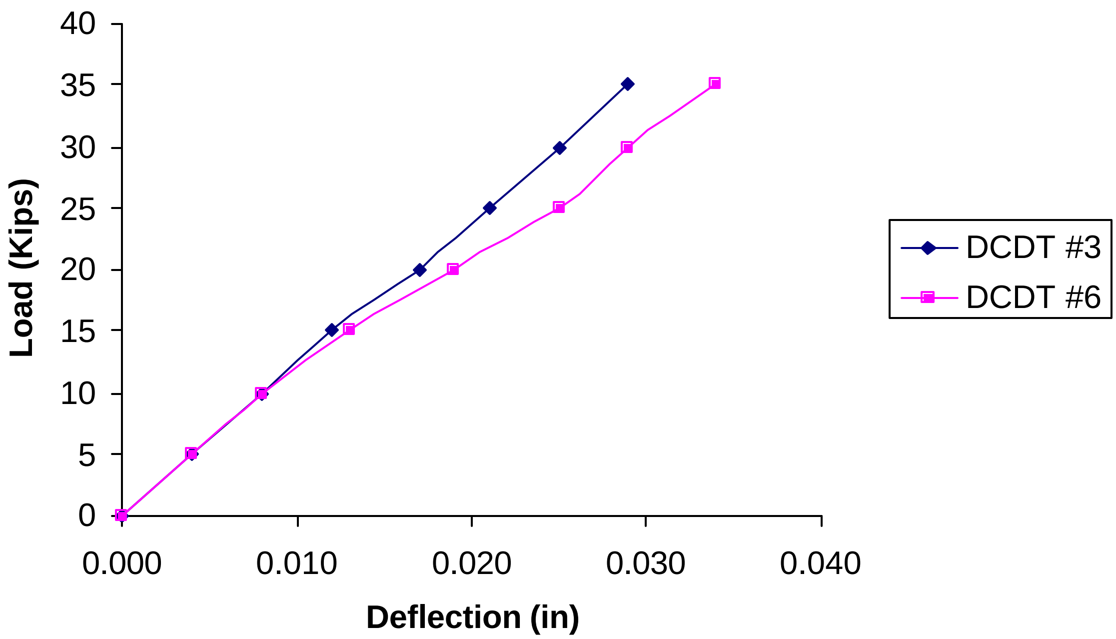

Figure B-28 Fatigue Specimen #1 Main Bar #1-1350K Cycles

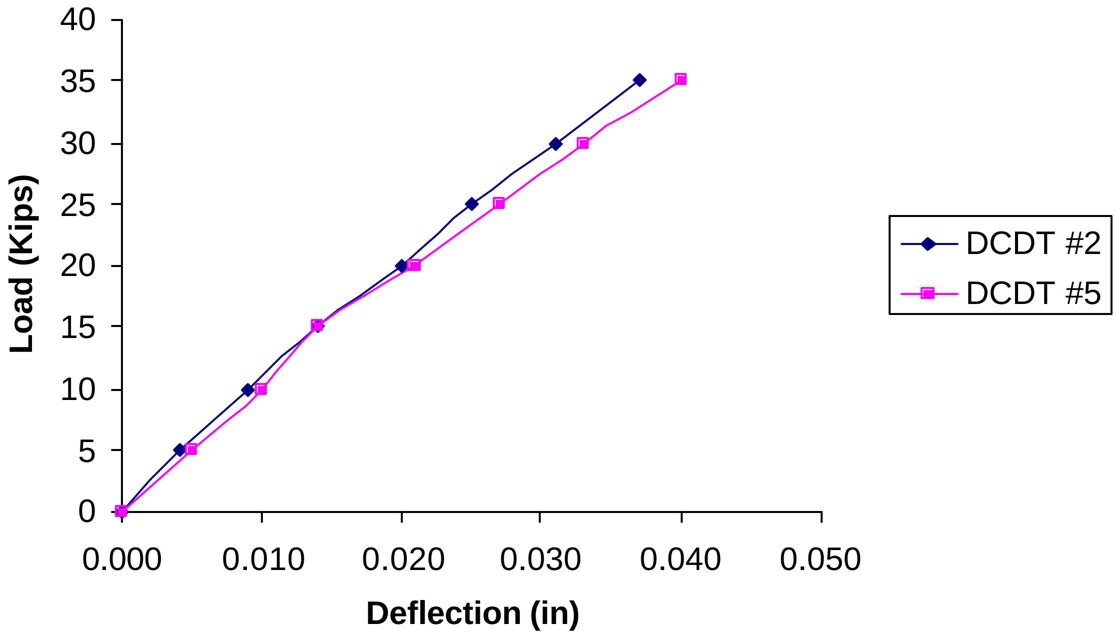

Figure B-29 Fatigue Specimen #1 Main Bar #2-1350K Cycles

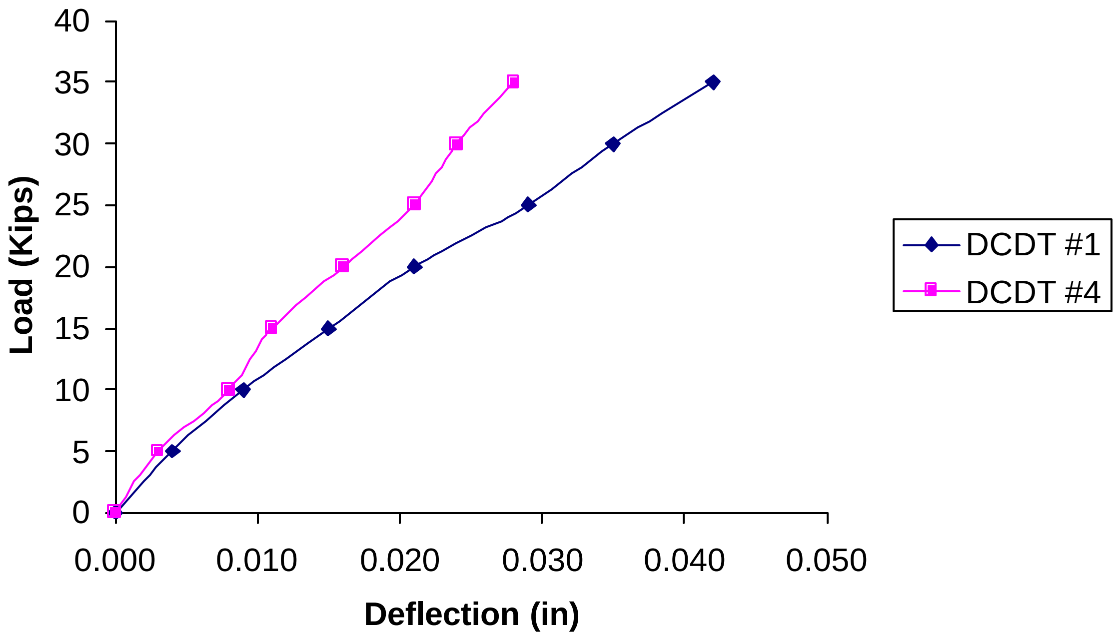

Figure B-30 Fatigue Specimen #1 Main Bar #3-1350K Cycles

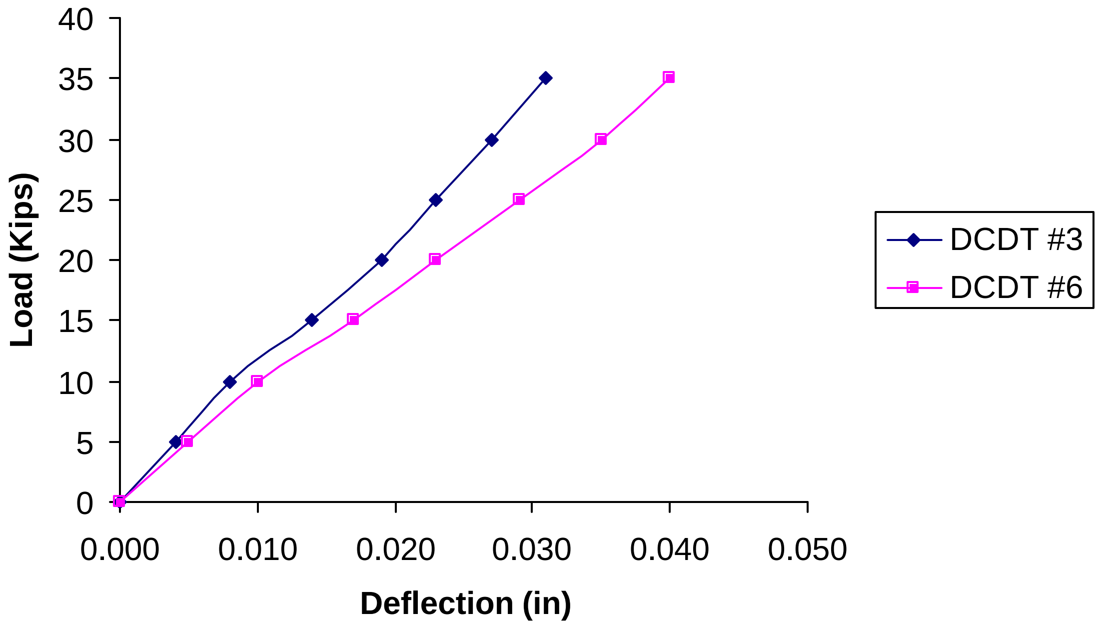

Figure B-31 Fatigue Specimen #1 Main Bar #1-1500K Cycles

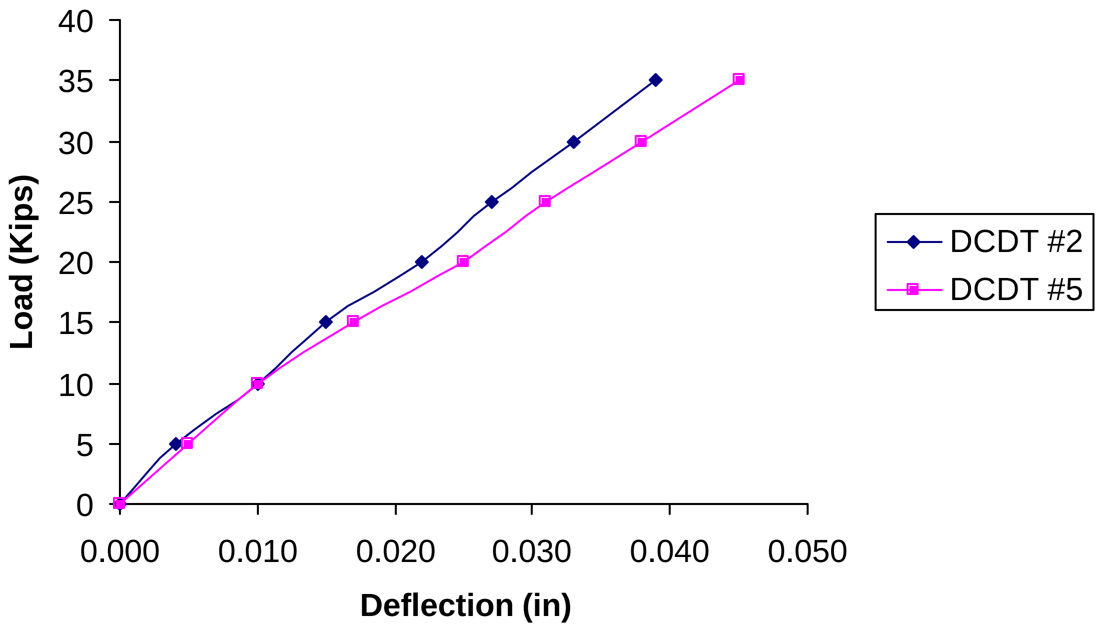

Figure B-32 Fatigue Specimen #1 Main Bar #2-1500K Cycles

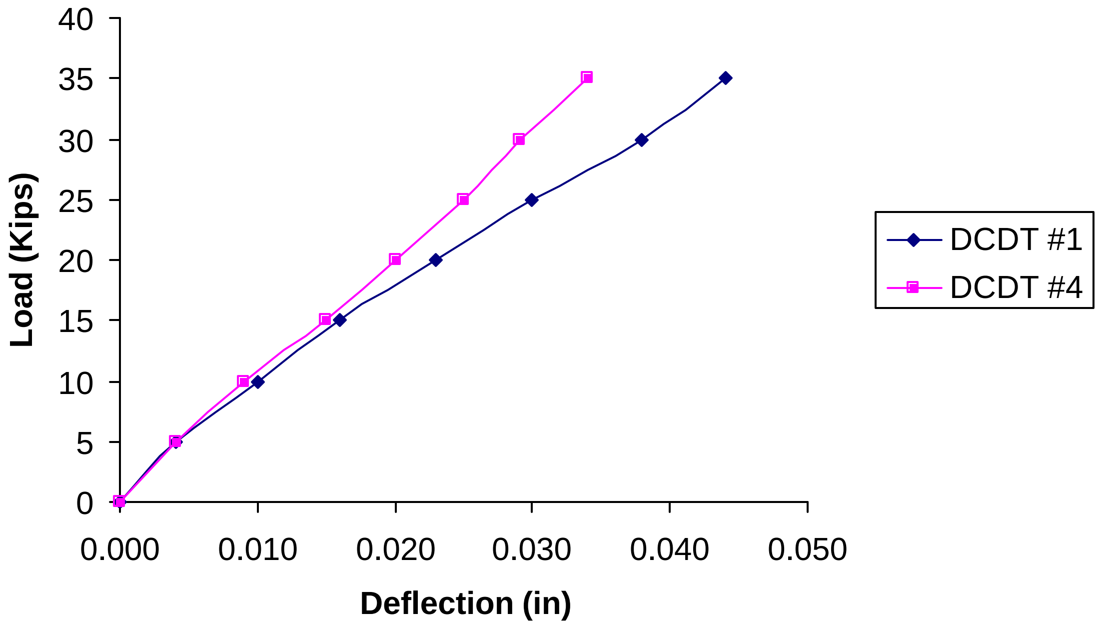

Figure B-33 Fatigue Specimen #1 Main Bar #3-1500K Cycles

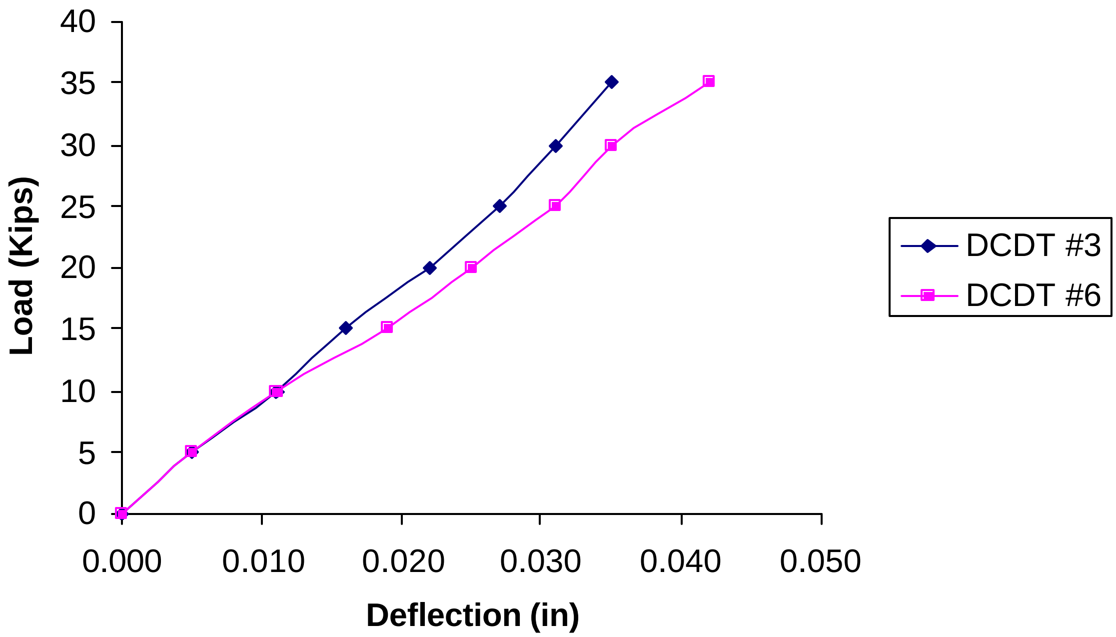

Figure B-34 Fatigue Specimen #1 Main Bar #1-1650K Cycles

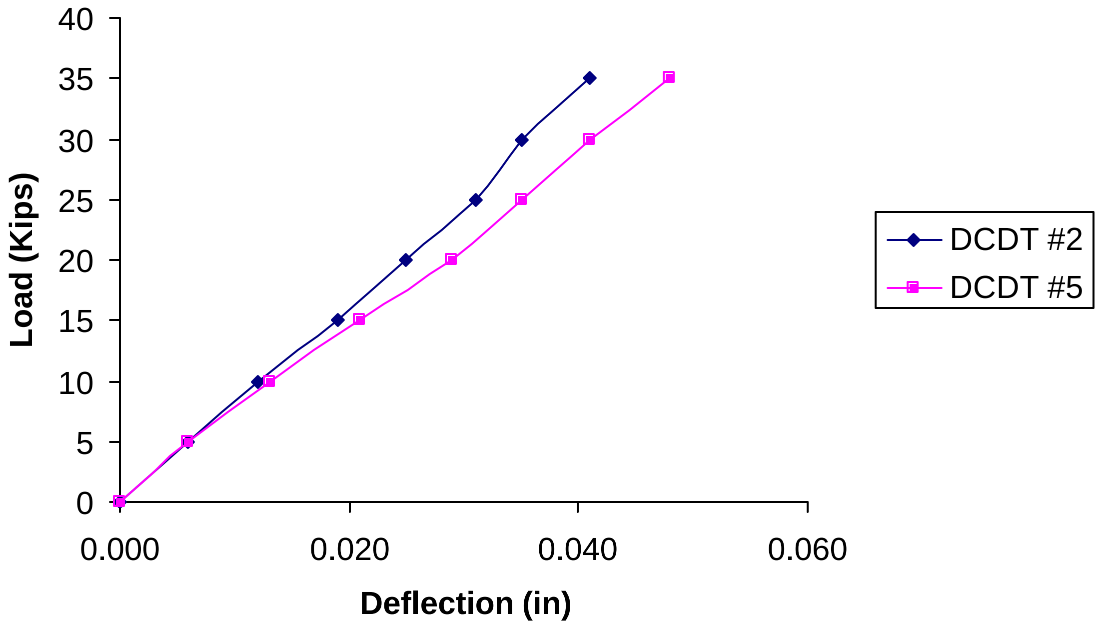

Figure B-35 Fatigue Specimen #1 Main Bar #2-1650K Cycles

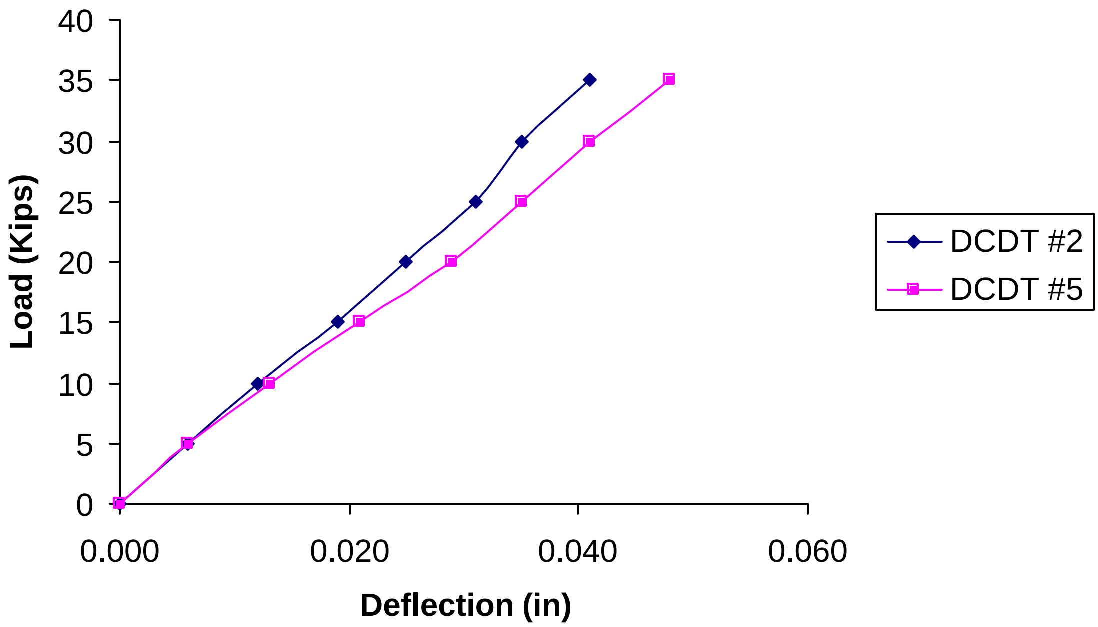

Figure B-36 Fatigue Specimen #1 Main Bar #3-1650K Cycles

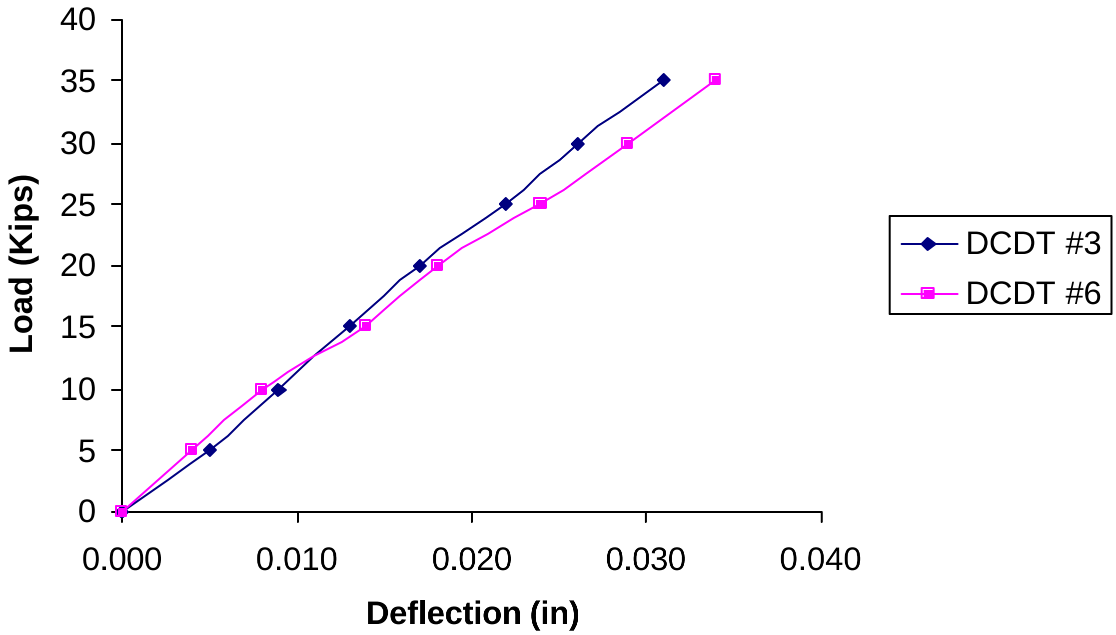

Figure B-37 Fatigue Specimen #1 Main Bar #1-1800K Cycles

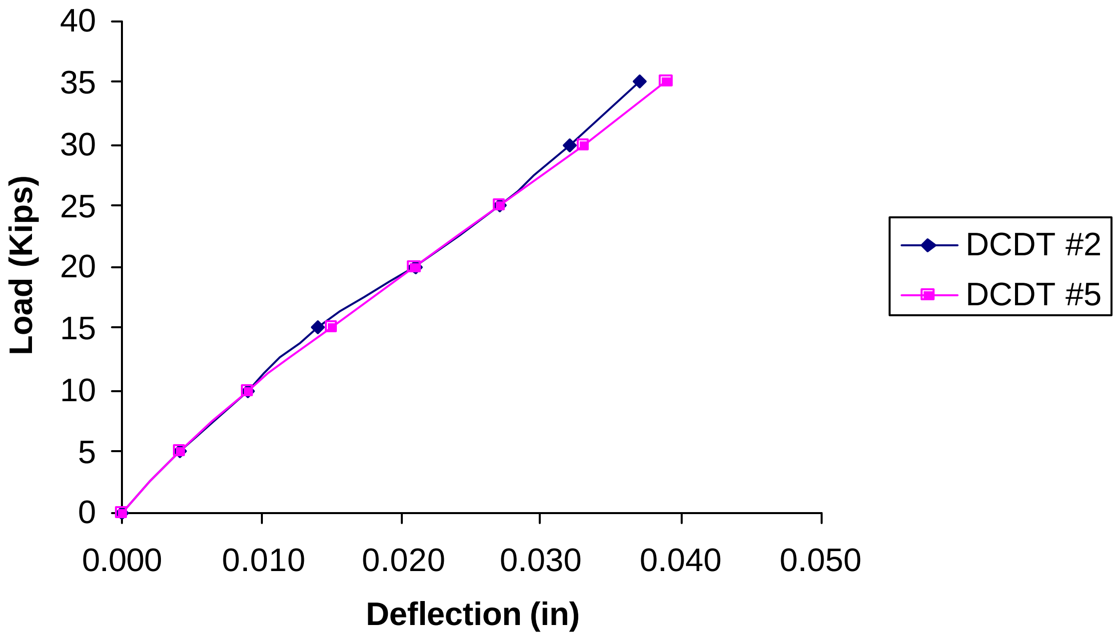

Figure B-38 Fatigue Specimen #1 Main Bar #2-1800K Cycles

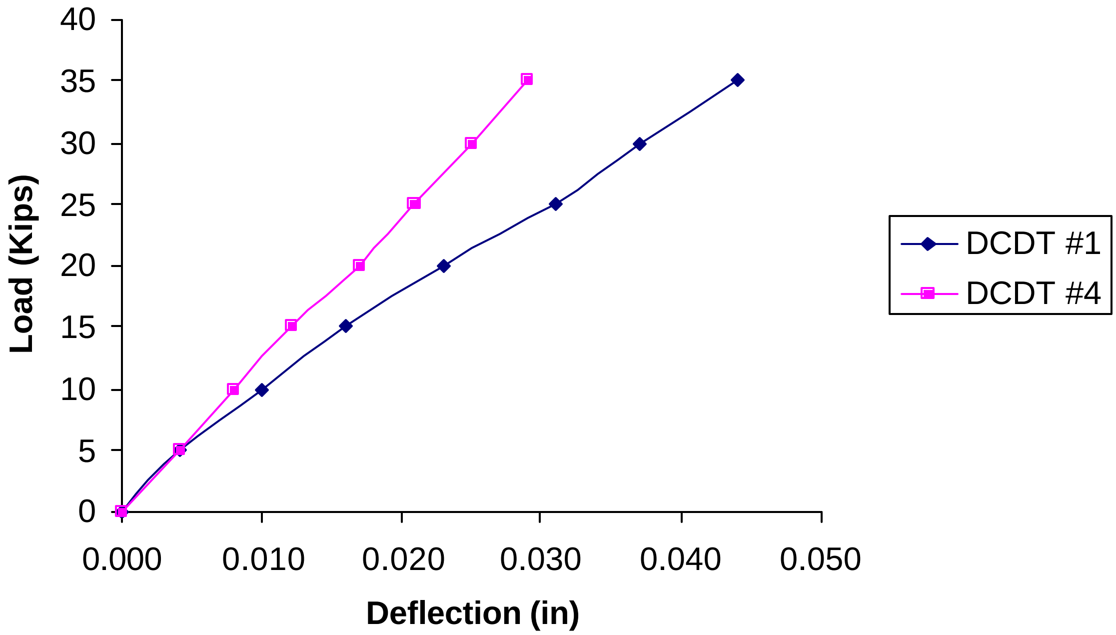

Figure B-39 Fatigue Specimen #1 Main Bar #3-1800K Cycles

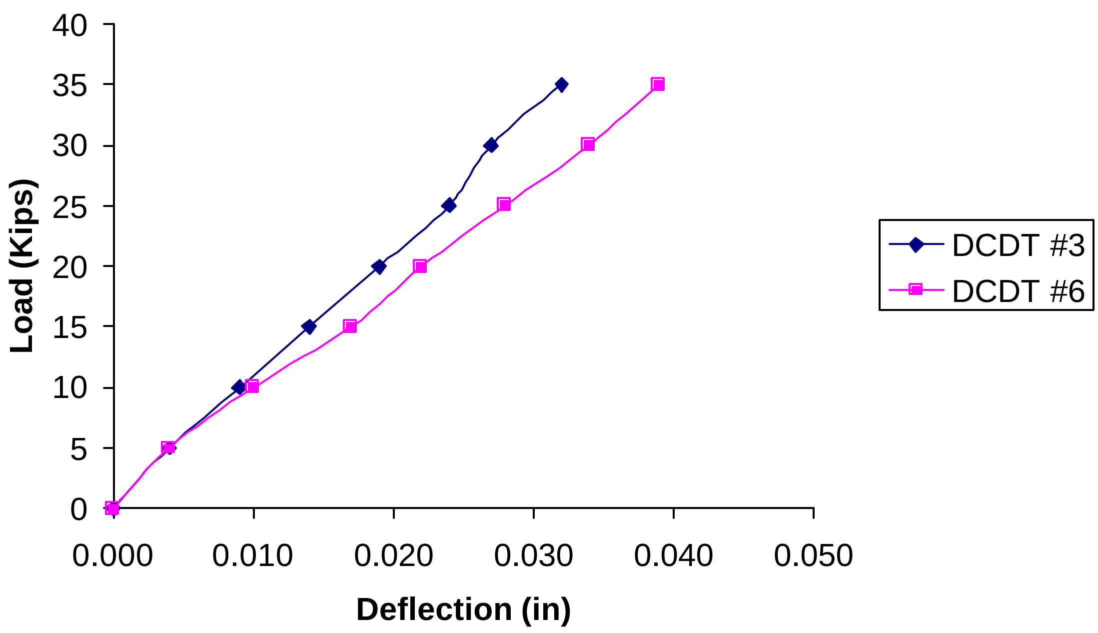

Figure B-40 Fatigue Specimen #1 Main Bar #1-1950K Cycles

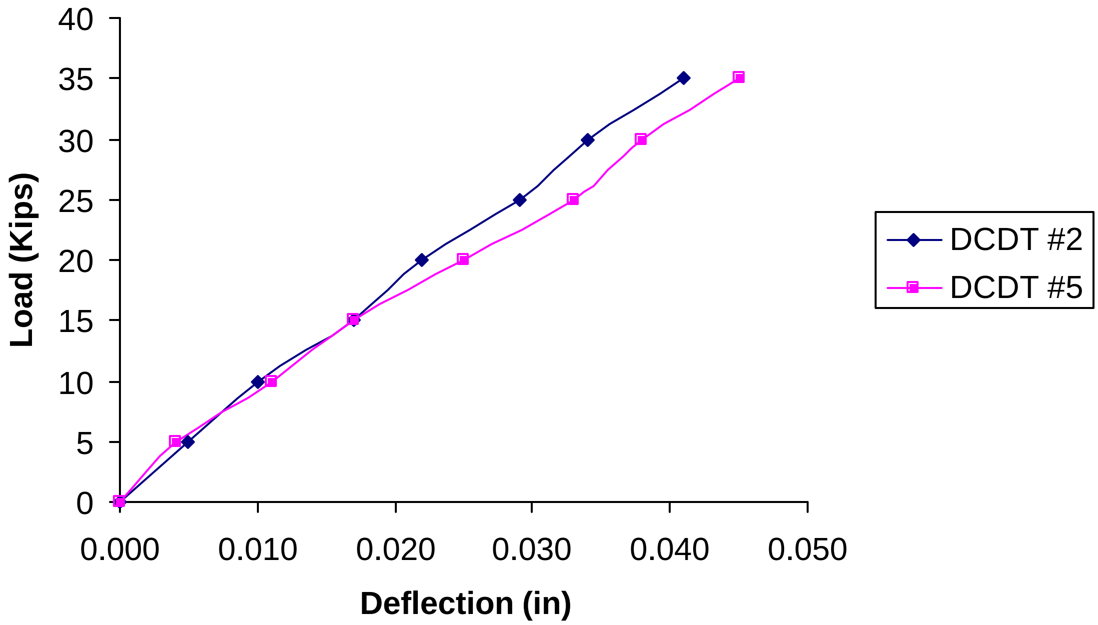

Figure B-41 Fatigue Specimen #1 Main Bar #2-1950K Cycles

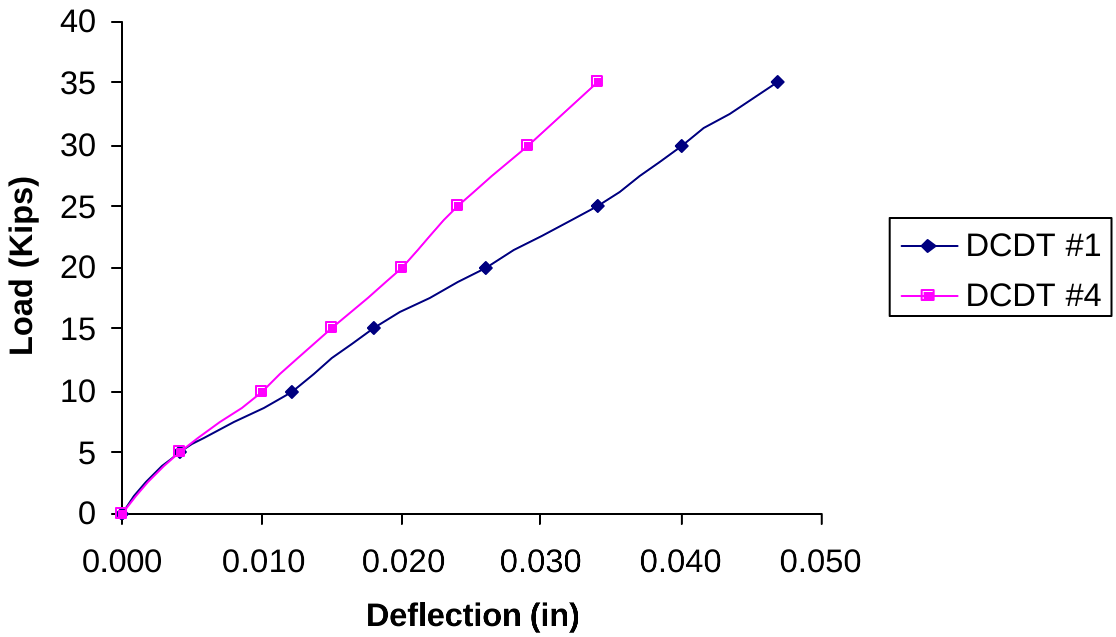

Figure B-42 Fatigue Specimen #1 Main Bar #3-1950K Cycles

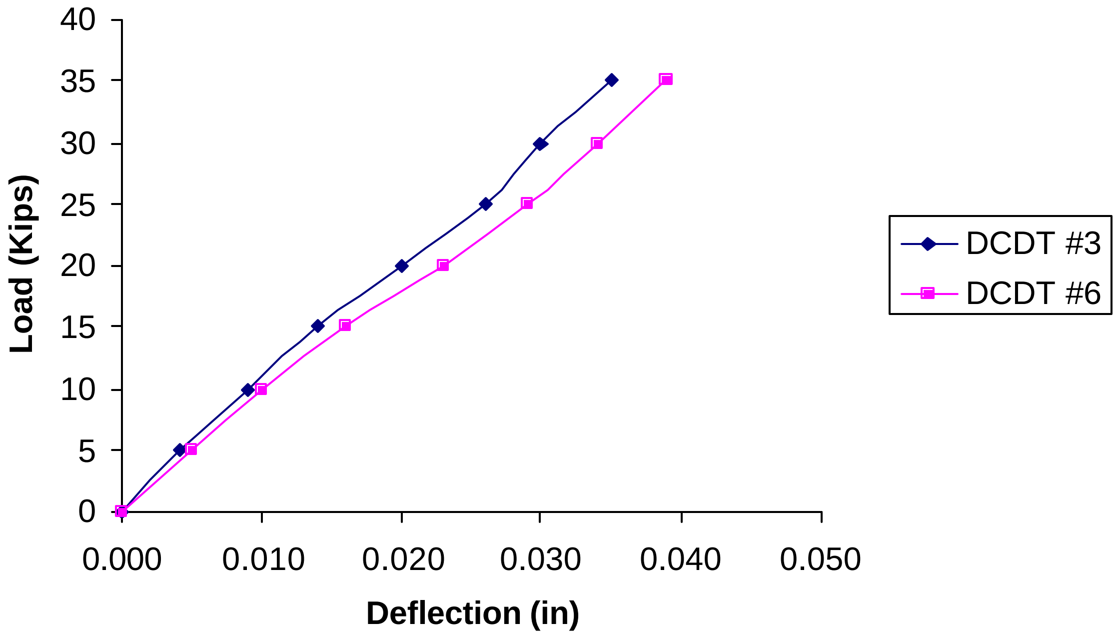

Figure B-43 Fatigue Specimen #1 Main Bar #1-2100K Cycles

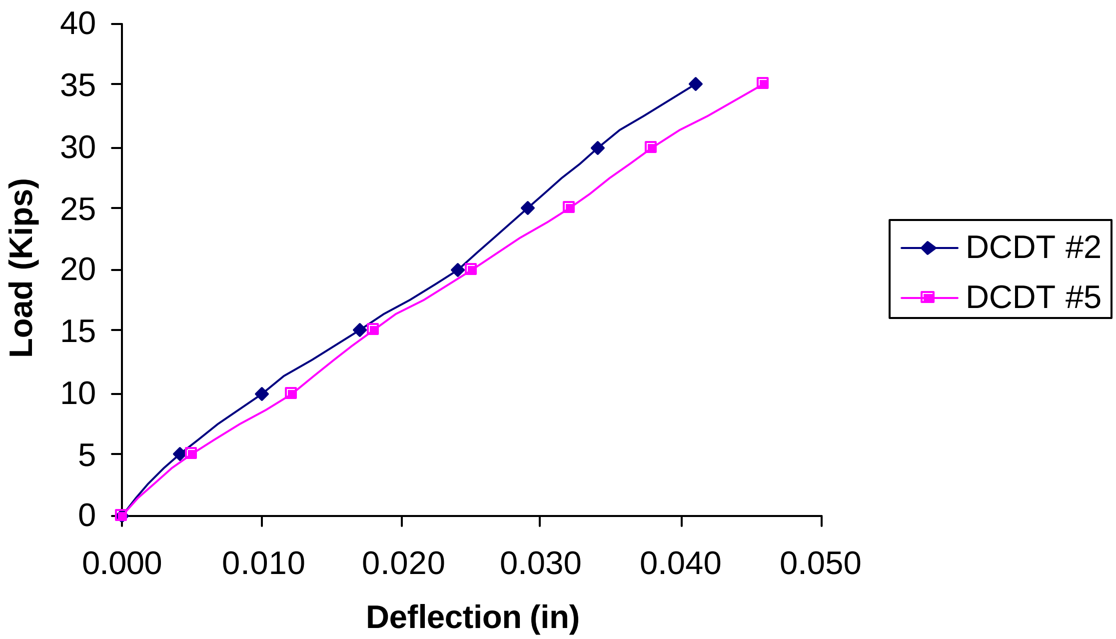

Figure B-44 Fatigue Specimen #1 Main Bar #2-2100K Cycles

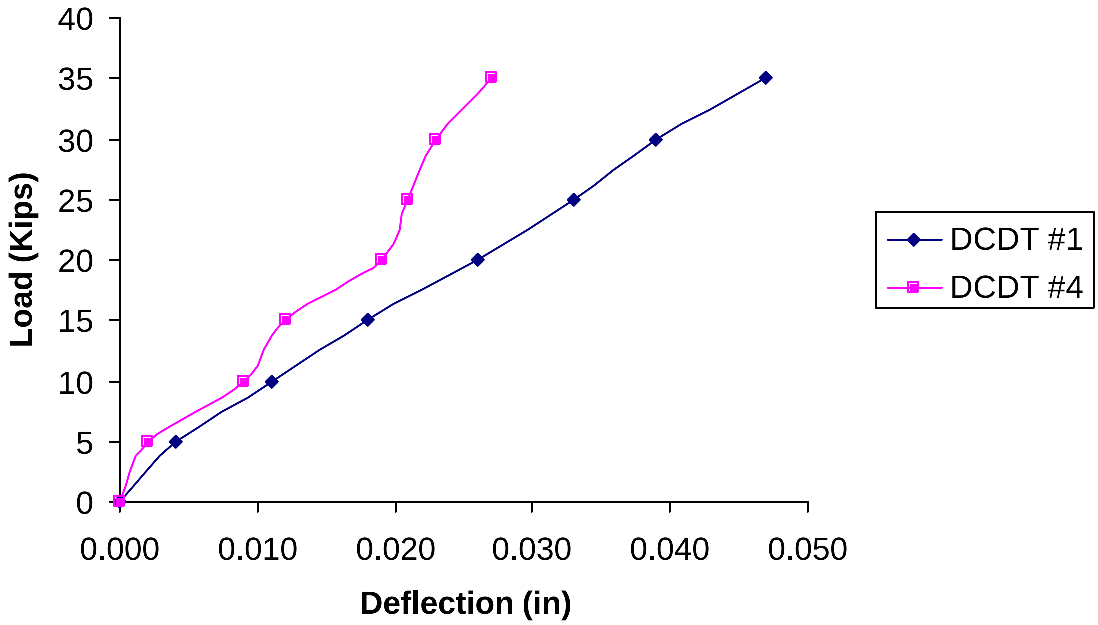

Figure B-45 Fatigue Specimen #1 Main Bar #3-2100K Cycles

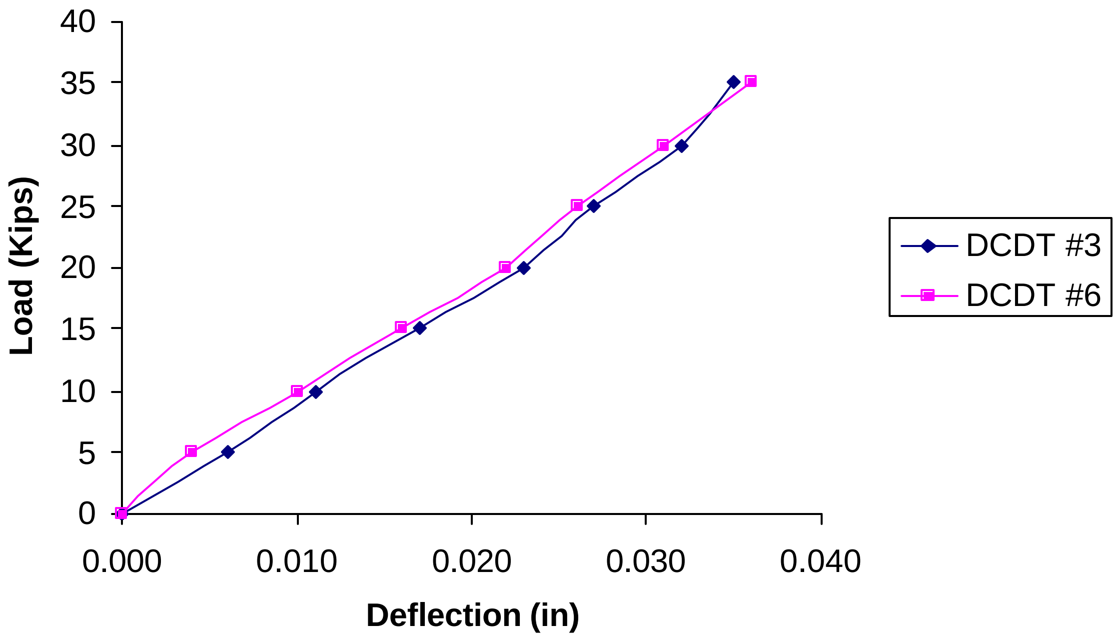

Figure B-46 Fatigue Specimen #1 Main Bar #1-2250K Cycles

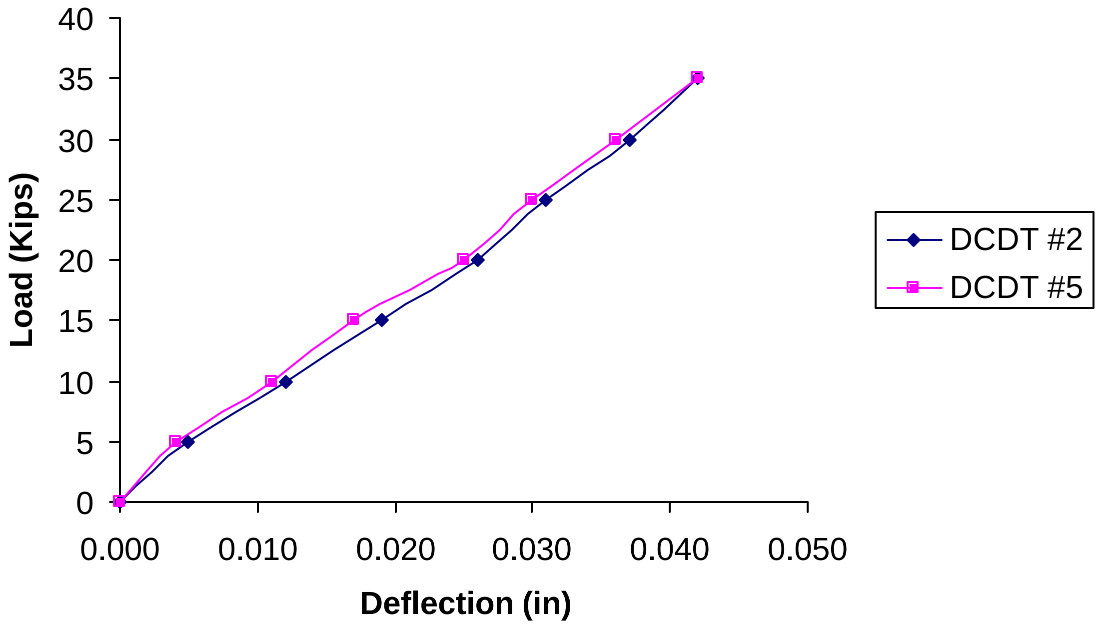

Figure B-47 Fatigue Specimen #1 Main Bar #2-2250K Cycles

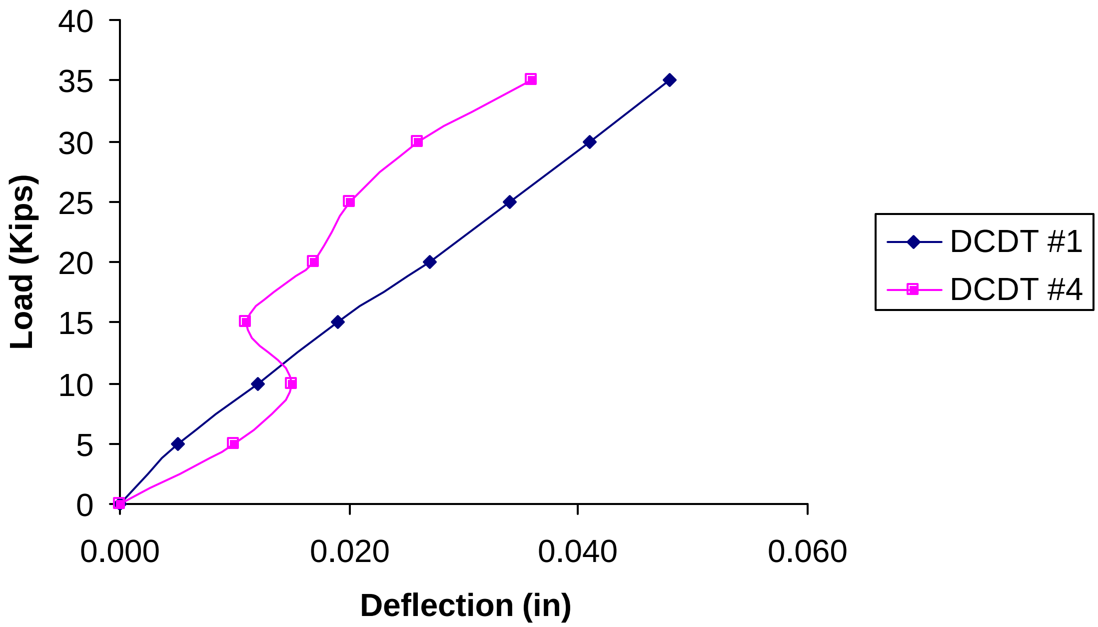

Figure B-48 Fatigue Specimen #1 Main Bar #3-2250K Cycles

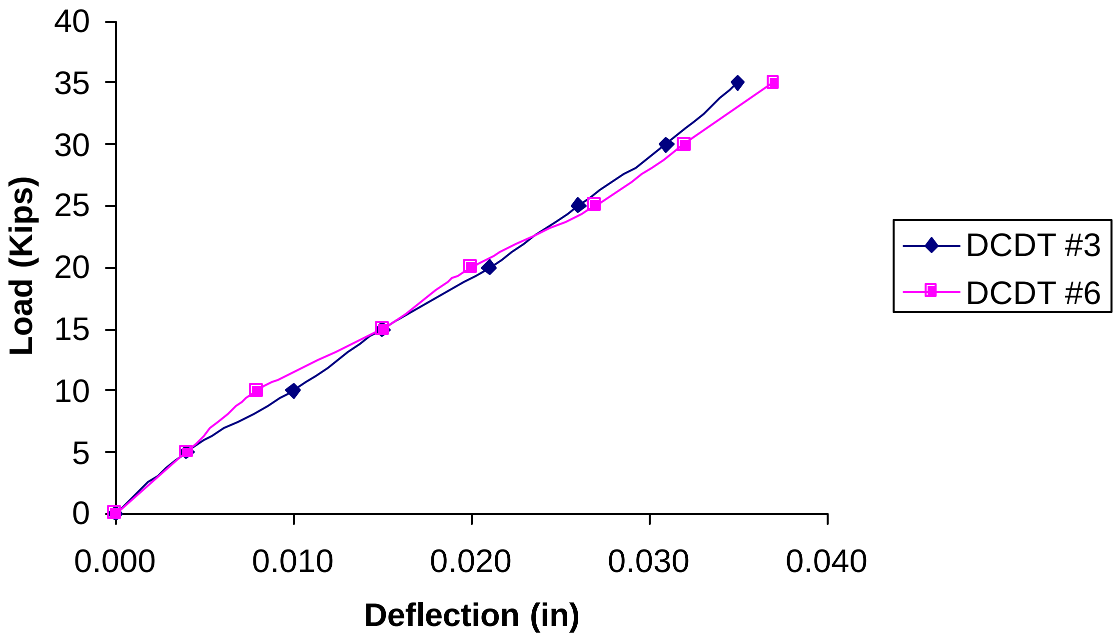

Figure B-49 Fatigue Specimen #1 Main Bar #1-2400K Cycles

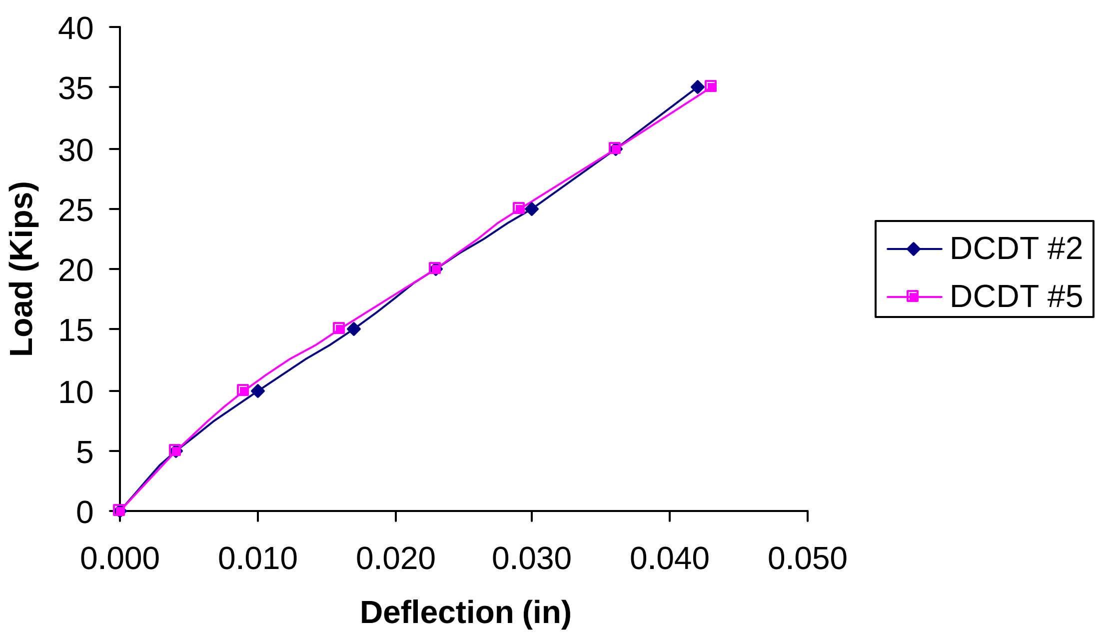

Figure B-50 Fatigue Specimen #1 Main Bar #2-2400K Cycles

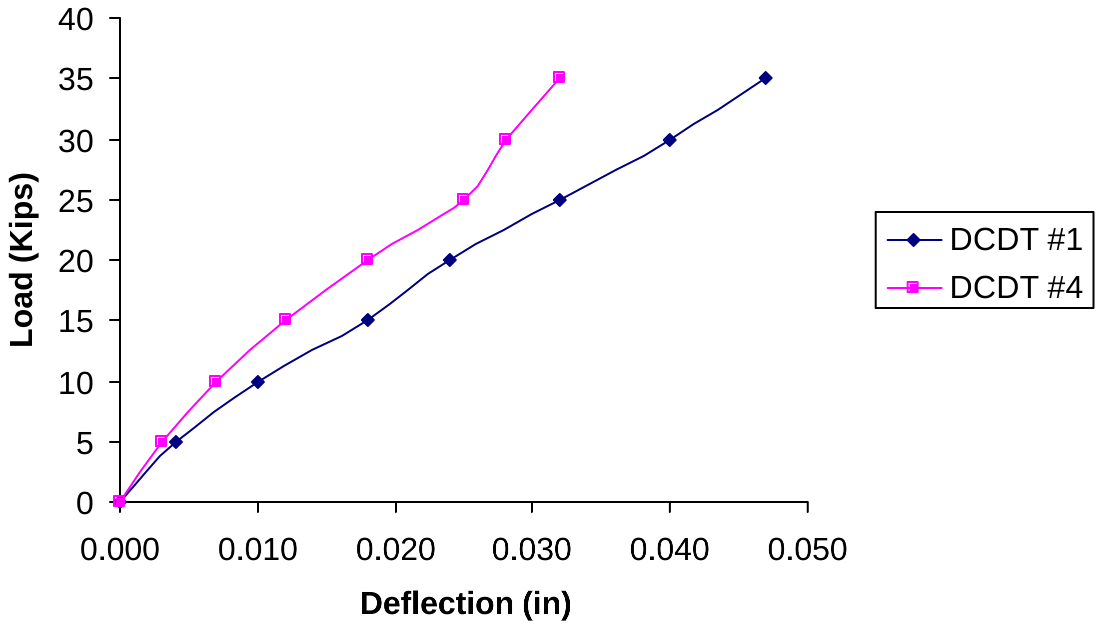

Figure B-51 Fatigue Specimen #1 Main Bar #3-2400K Cycles

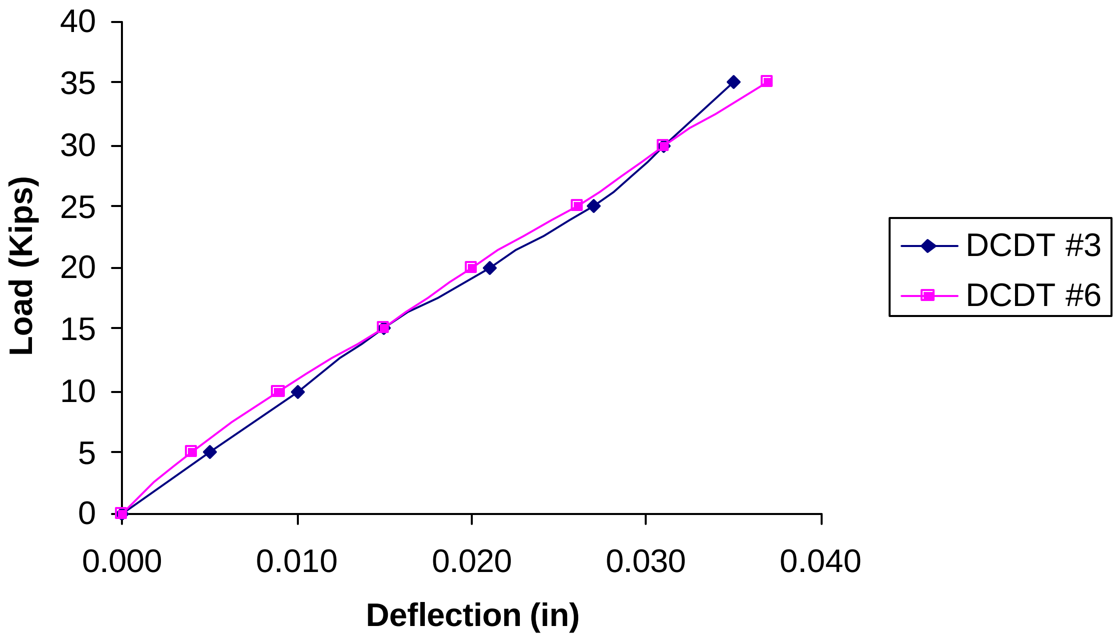

Figure B-52 Fatigue Specimen #1 Main Bar #1-2550K Cycles

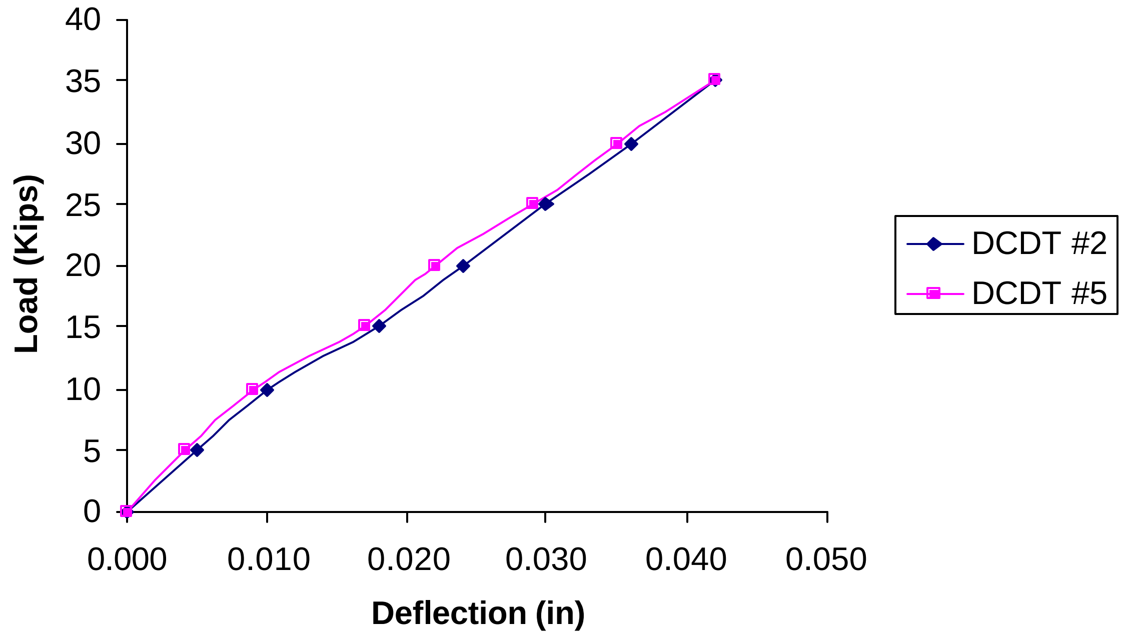

Figure B-53 Fatigue Specimen #1 Main Bar #2-2550K Cycles

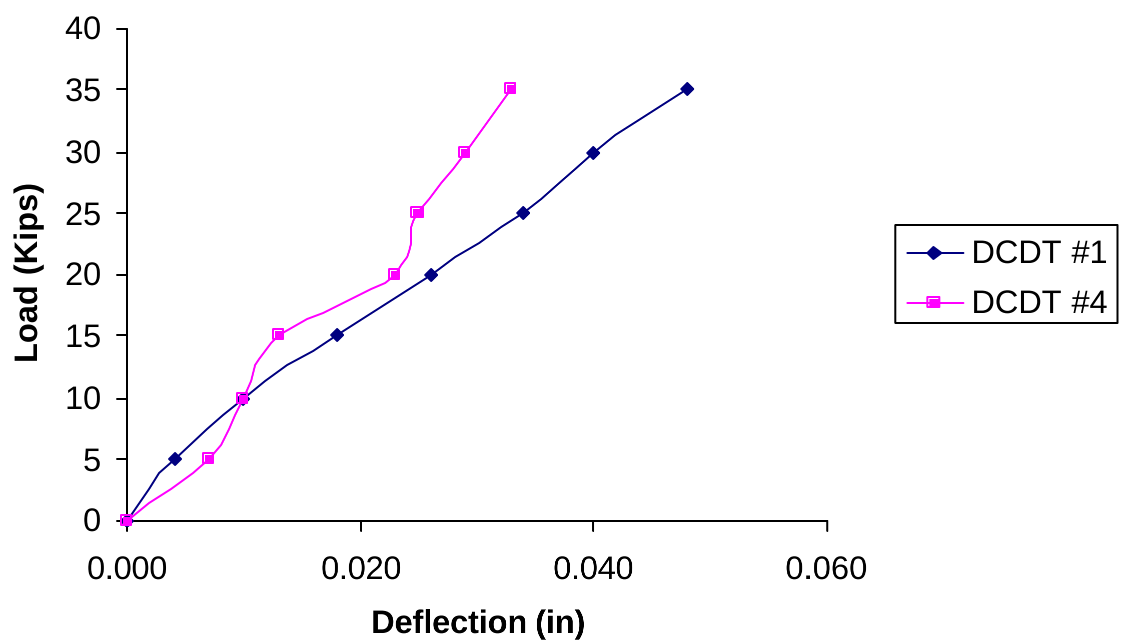

Figure B-54 Fatigue Specimen #1 Main Bar #3-2550K Cycles

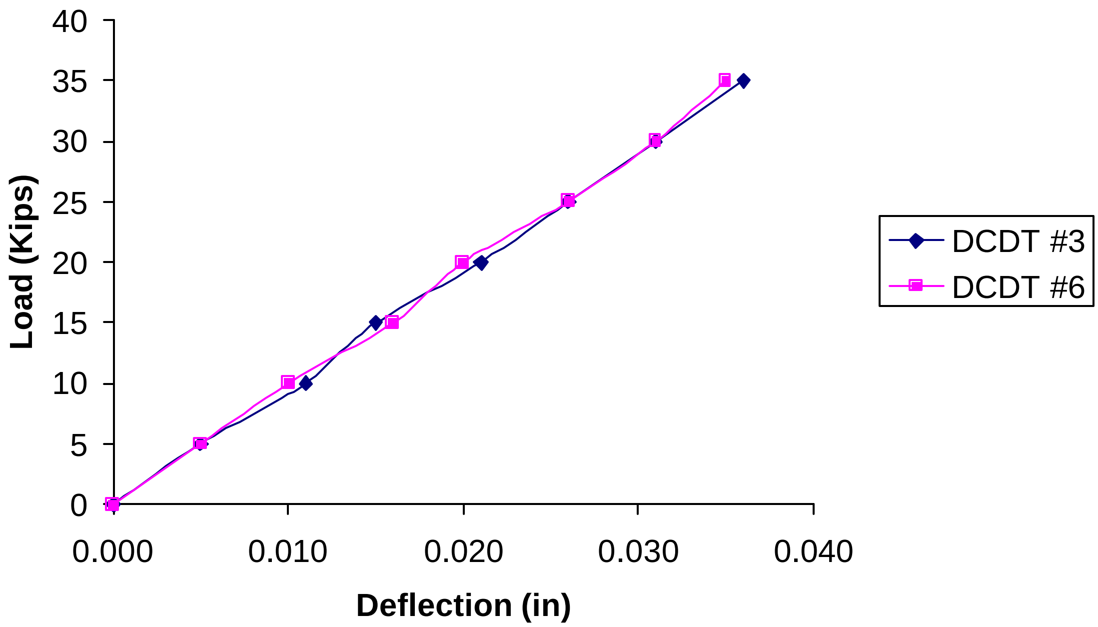

Figure B-55 Fatigue Specimen #1 Main Bar #1-2700K Cycles

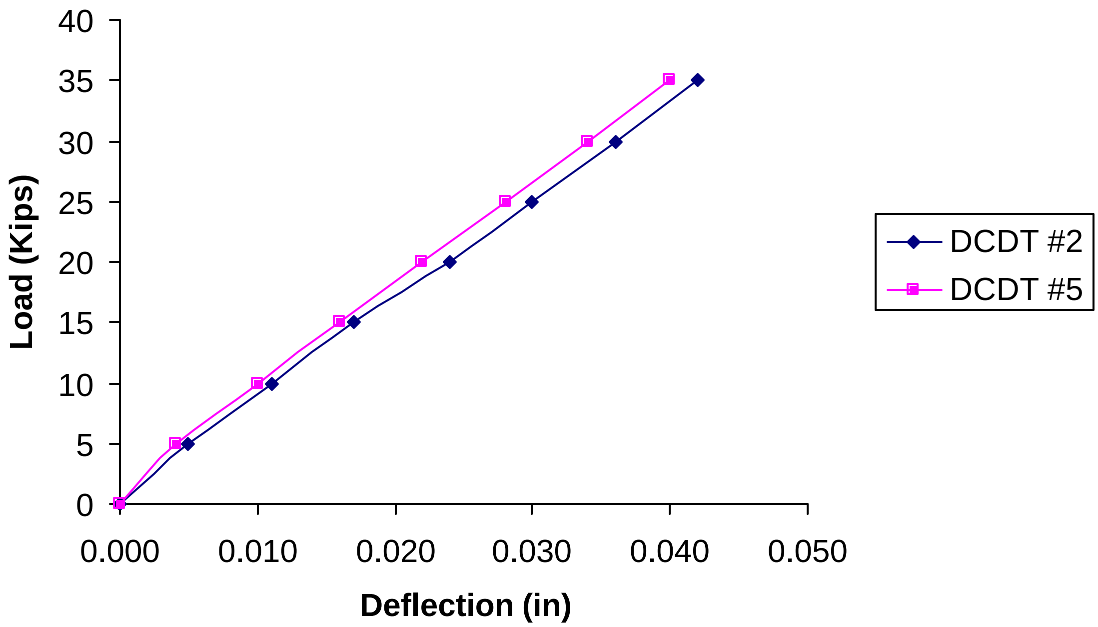

Figure B-56 Fatigue Specimen #1 Main Bar #2-2700K Cycles

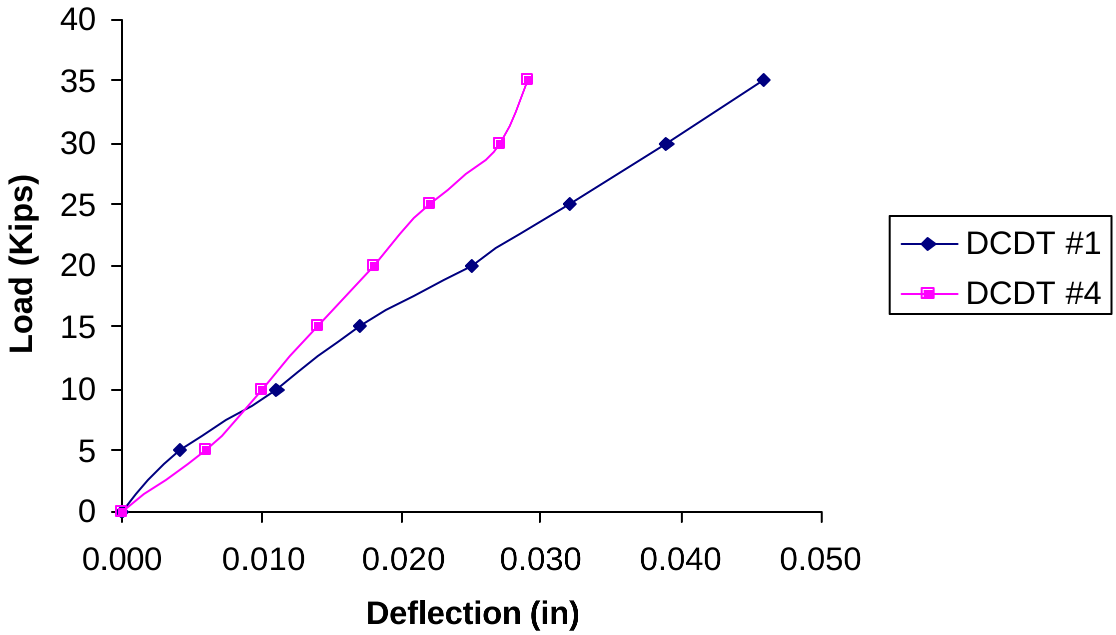

Figure B-57 Fatigue Specimen #1 Main Bar #3-2700K Cycles

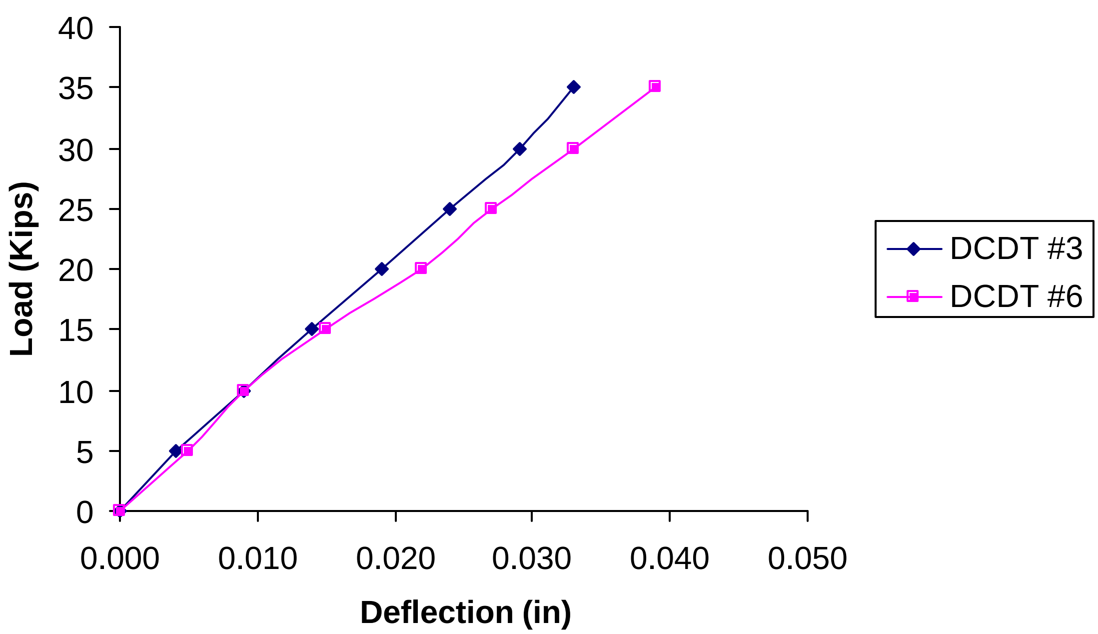

Figure B-58 Fatigue Specimen #1 Main Bar #1-2850K Cycles

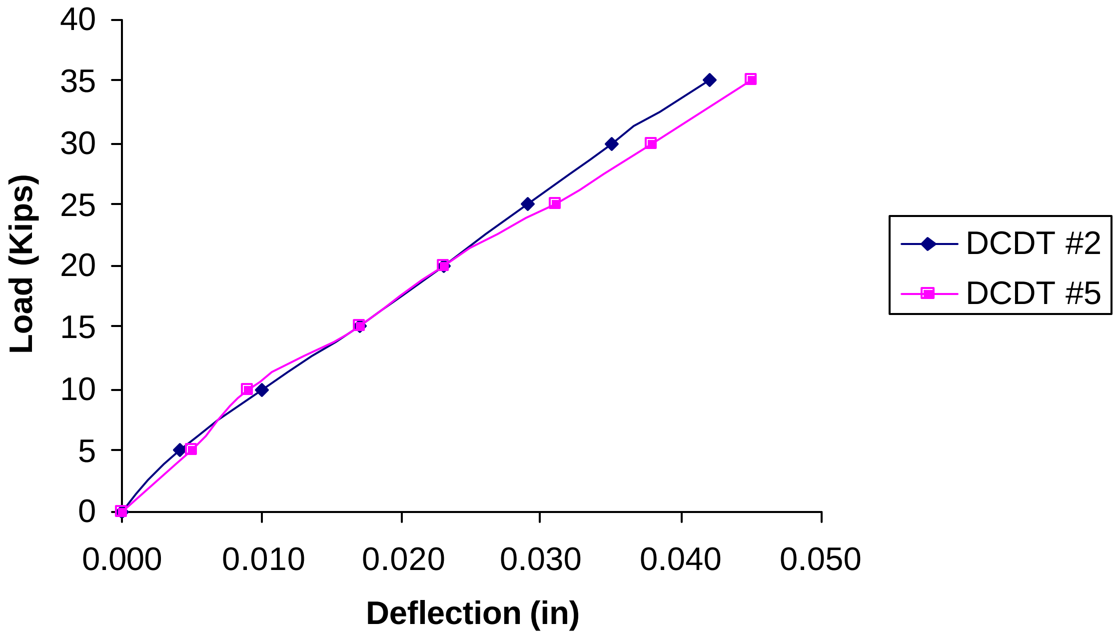

Figure B-59 Fatigue Specimen #1 Main Bar #2-2850K Cycles

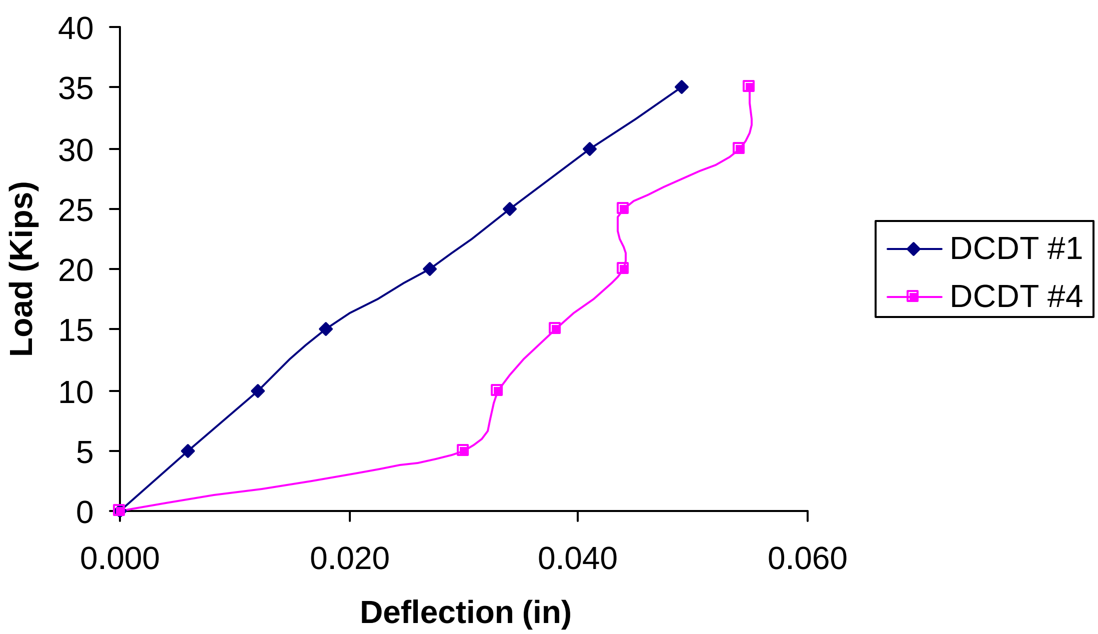

Figure B-60 Fatigue Specimen #1 Main Bar #3-2850K Cycles

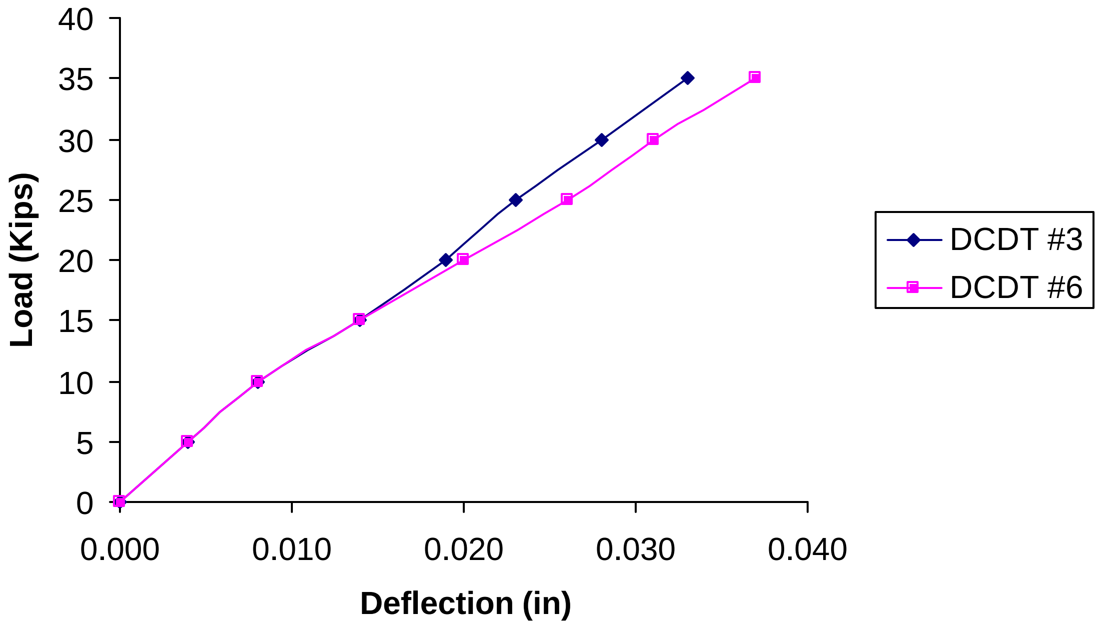

Figure B-61 Fatigue Specimen #1 Main Bar #1-3000K Cycles

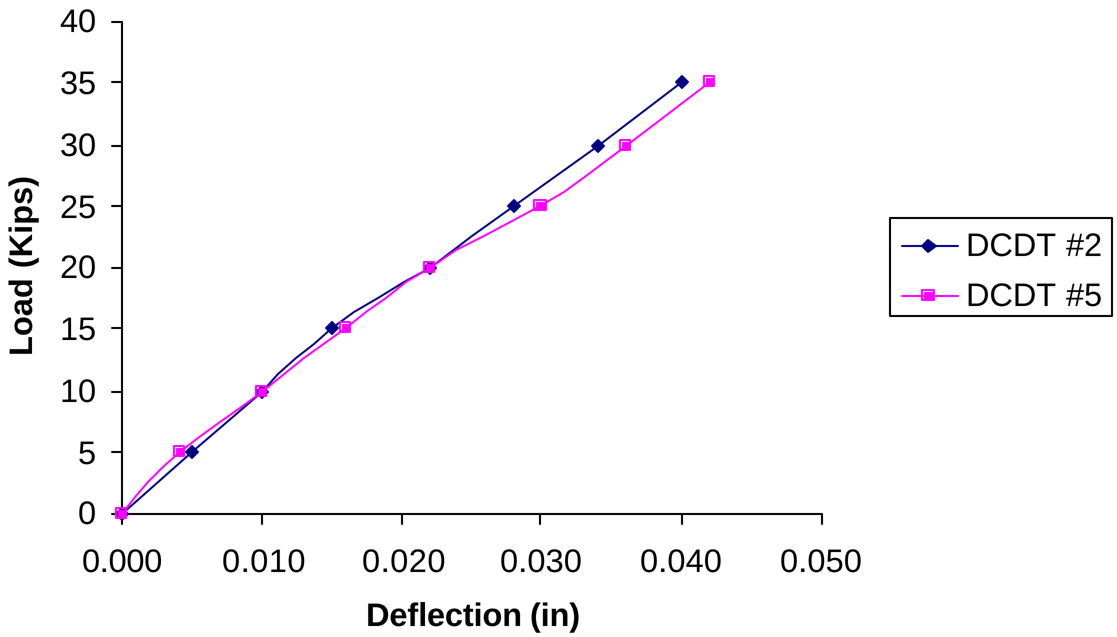

Figure B-62 Fatigue Specimen #1 Main Bar #2-3000K Cycles

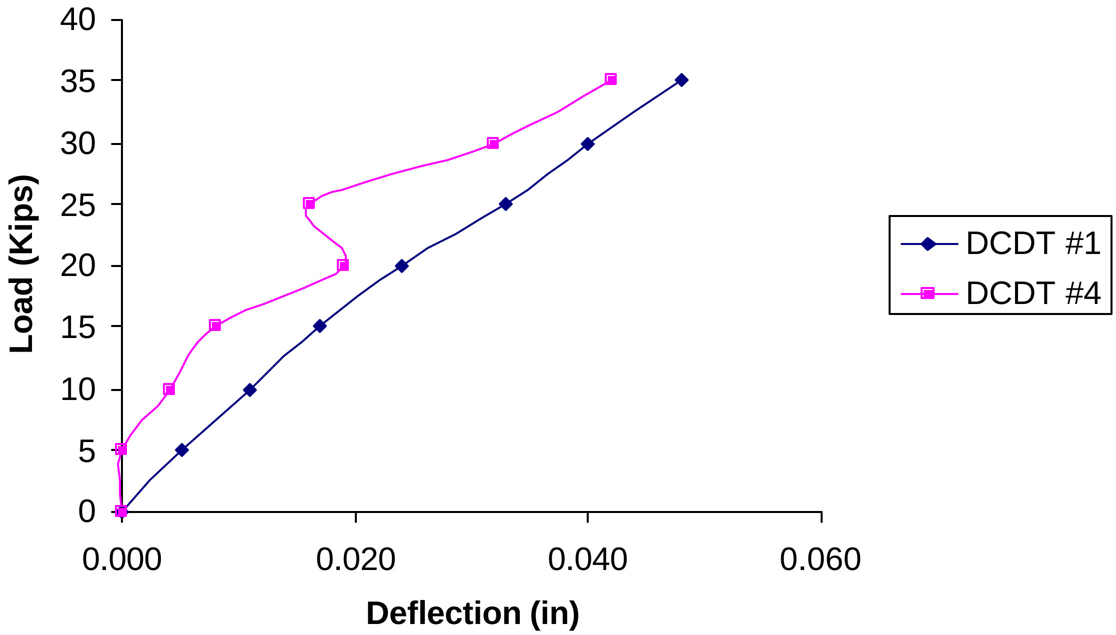

Figure B-63 Fatigue Specimen #1 Main Bar #3-3000K Cycles

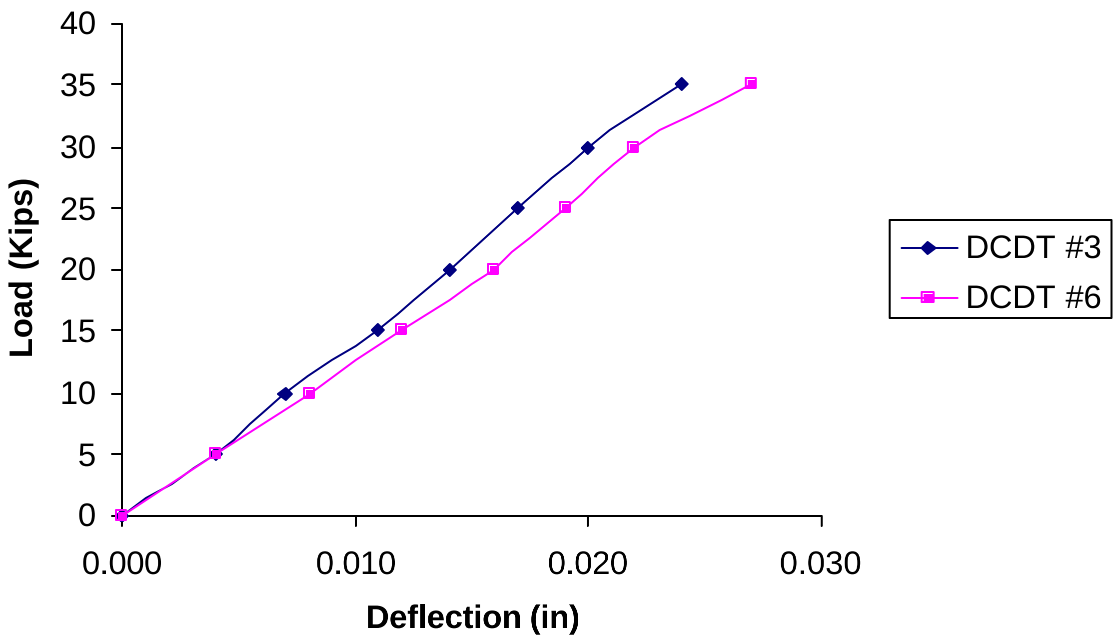

Figure B-64 Fatigue Specimen #1 Main Bar #1-3150K Cycles

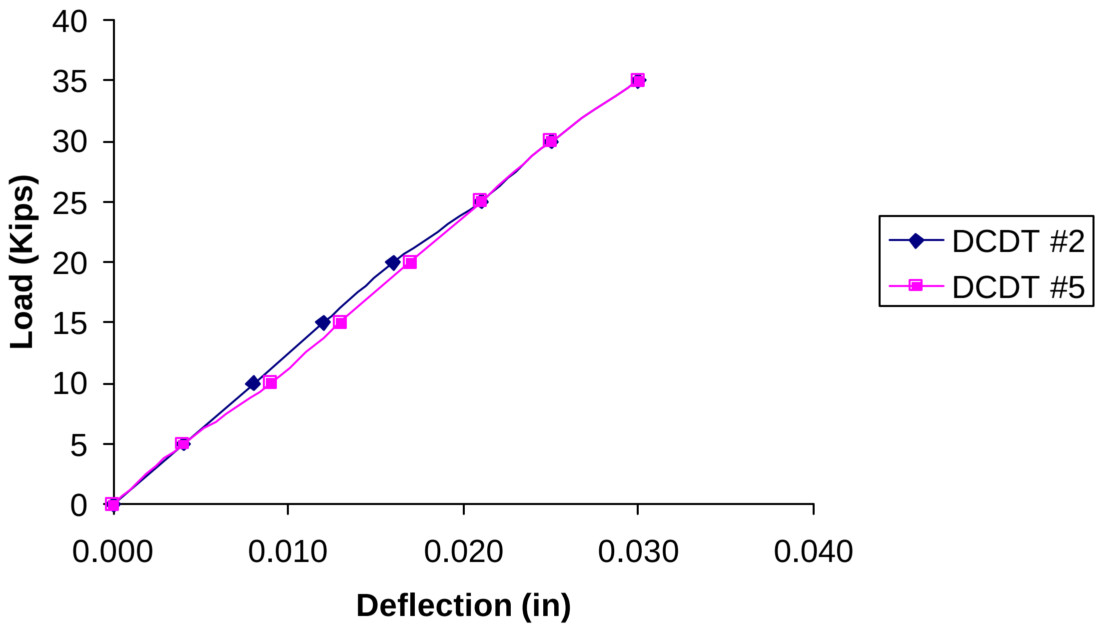

Figure B-65 Fatigue Specimen #1 Main Bar #2-3150K Cycles

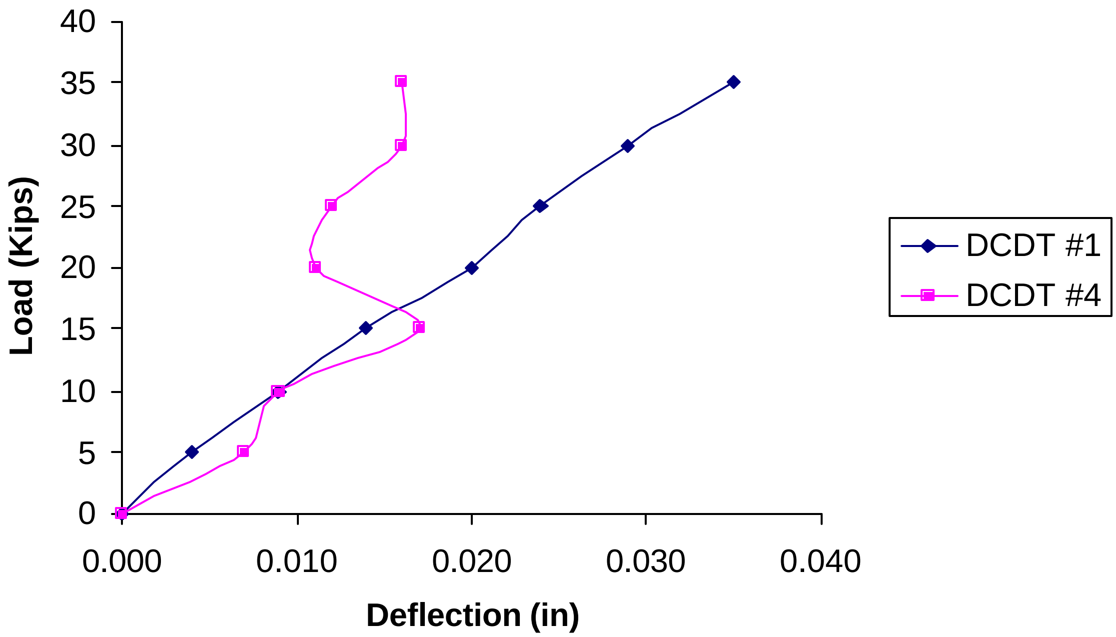

Figure B-66 Fatigue Specimen #1 Main Bar #3-3150K Cycles

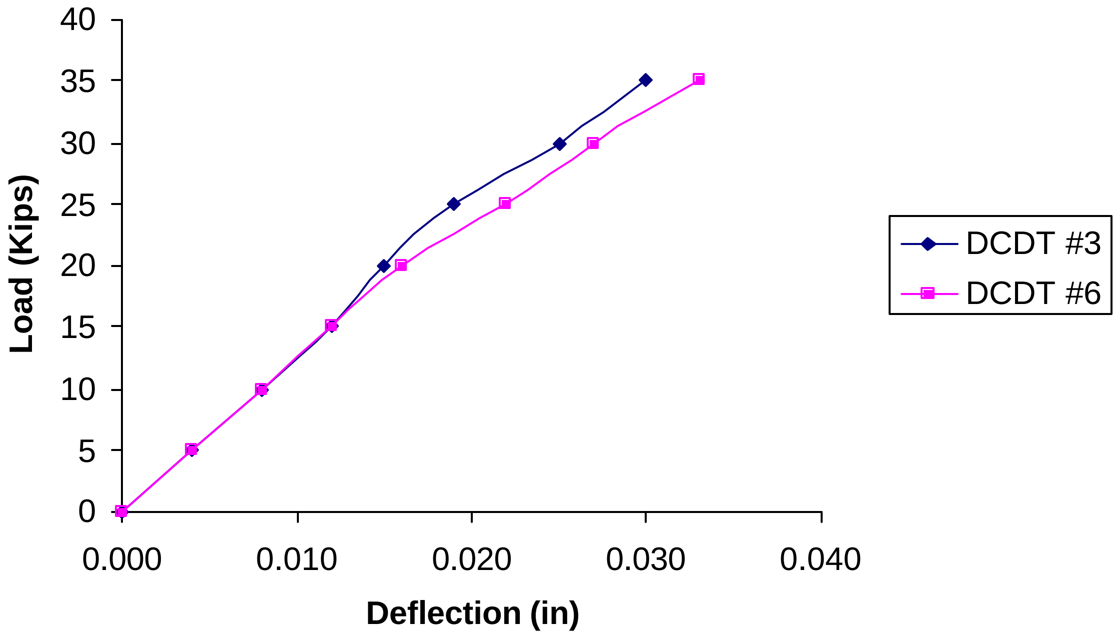

Figure B-67 Fatigue Specimen #1 Main Bar #1-3300K Cycles

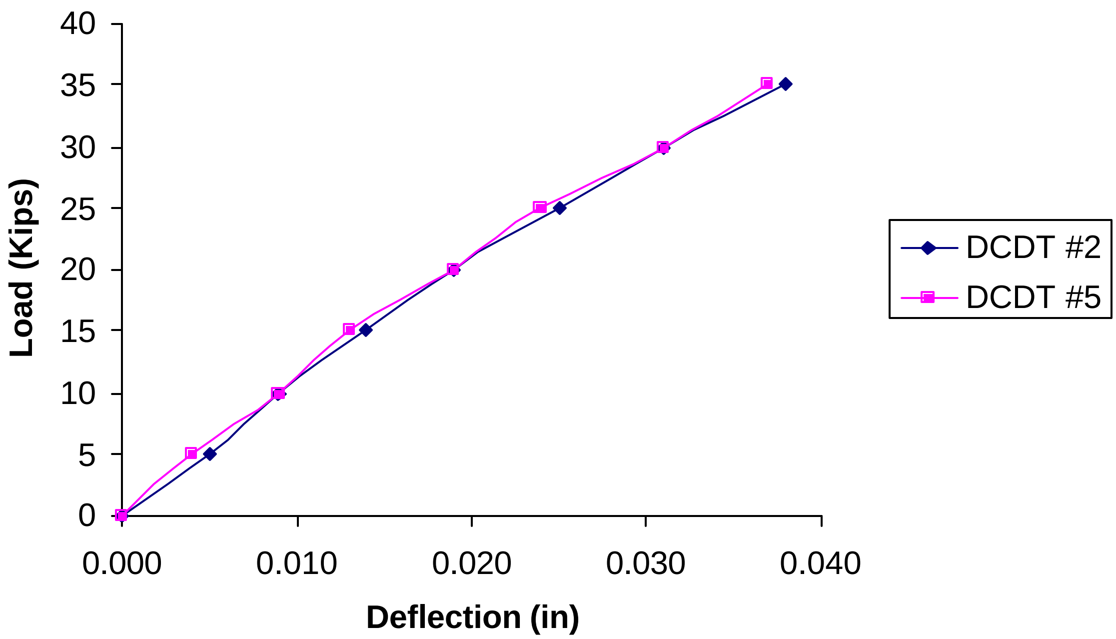

Figure B-68 Fatigue Specimen #1 Main Bar #2-3300K Cycles

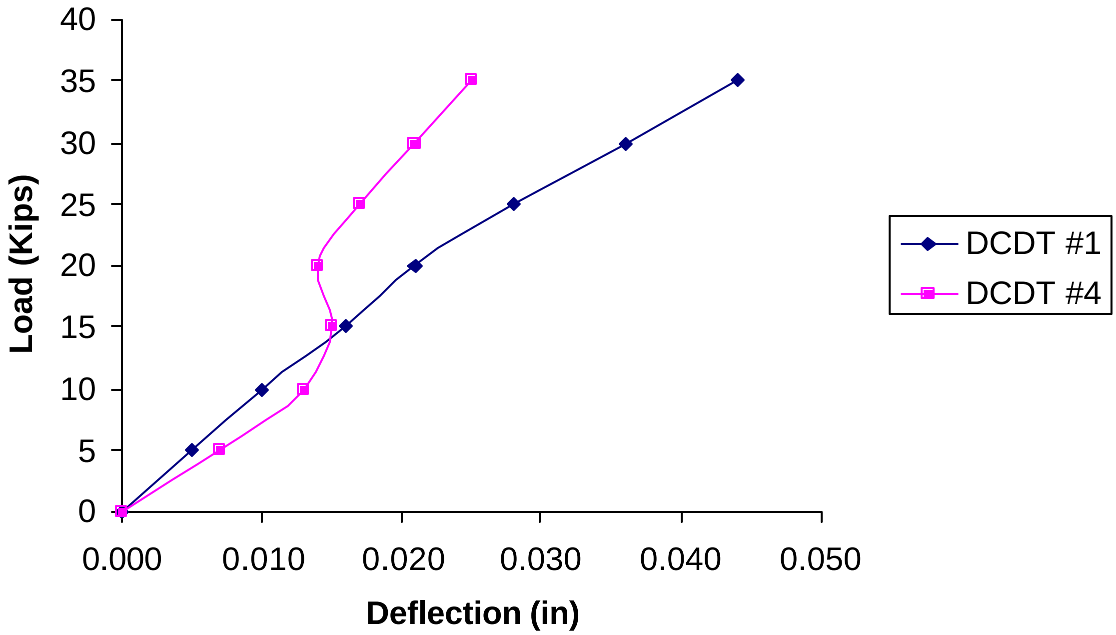

Figure B-69 Fatigue Specimen #1 Main Bar #3-3300K Cycles

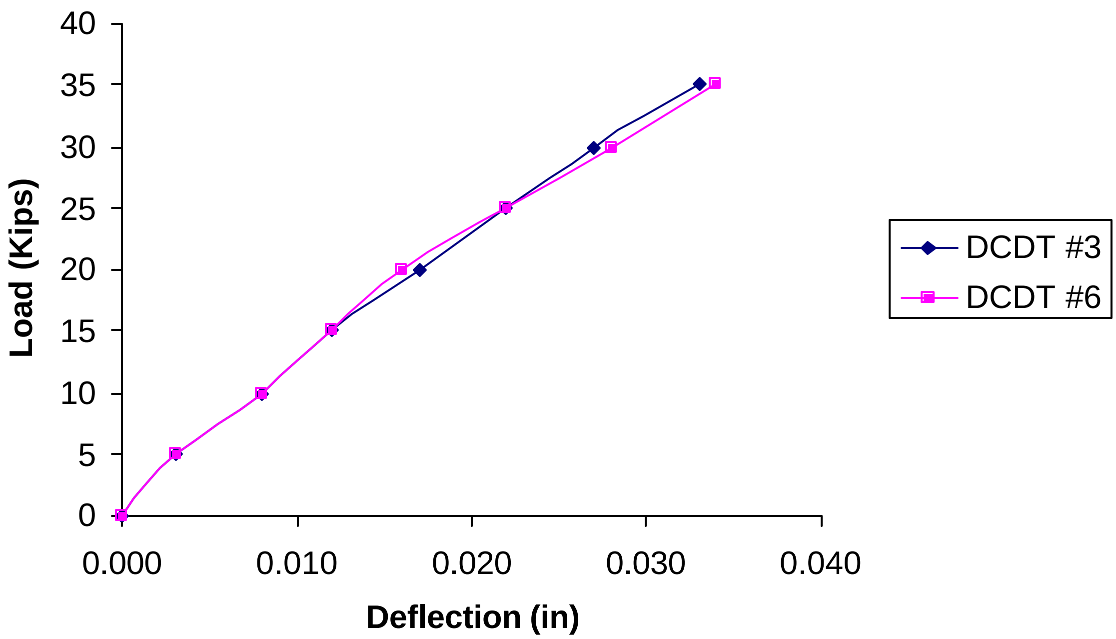

Figure B-70 Fatigue Specimen #1 Main Bar #1-3450K Cycles

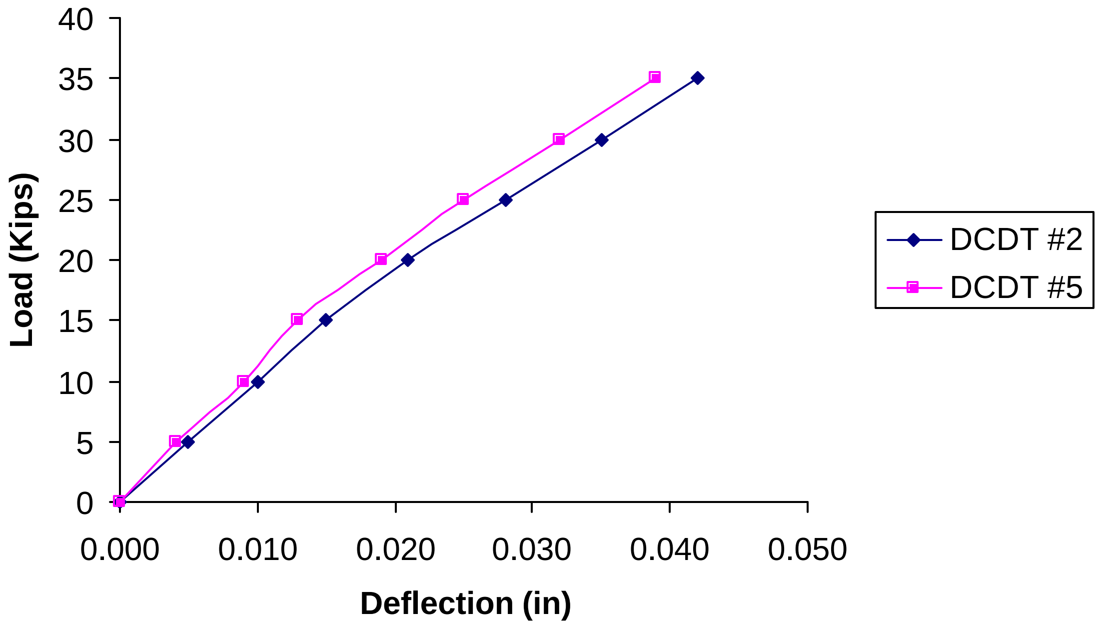

Figure B-71 Fatigue Specimen #1 Main Bar #2-3450K Cycles

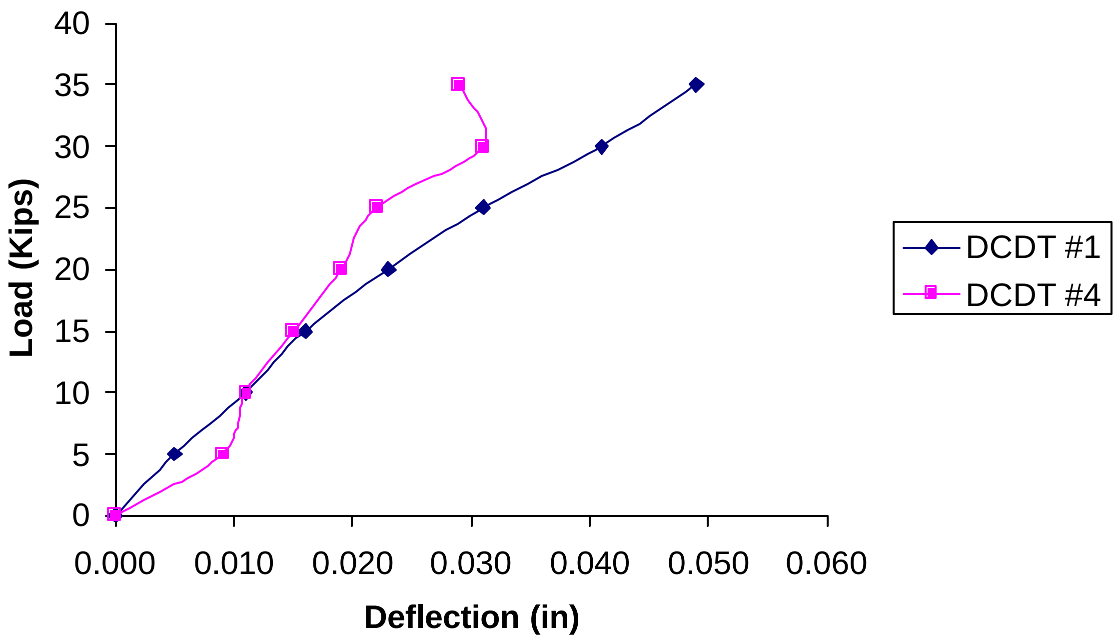

Figure B-72 Fatigue Specimen #1 Main Bar #3-3450K Cycles

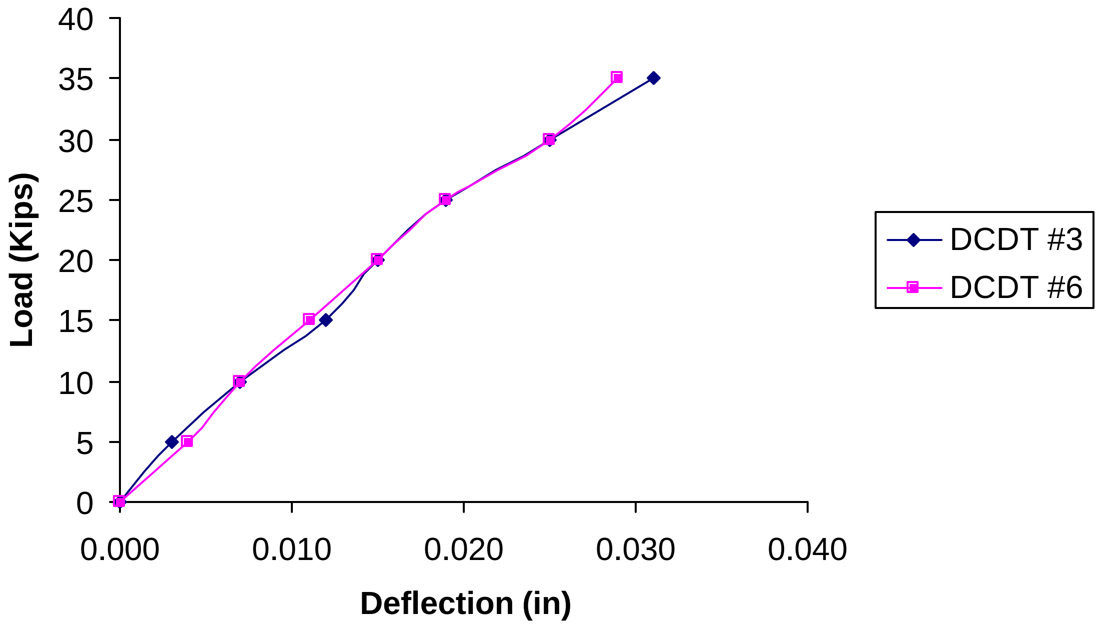

Figure B-73 Fatigue Specimen #1 Main Bar #1-3600K Cycles

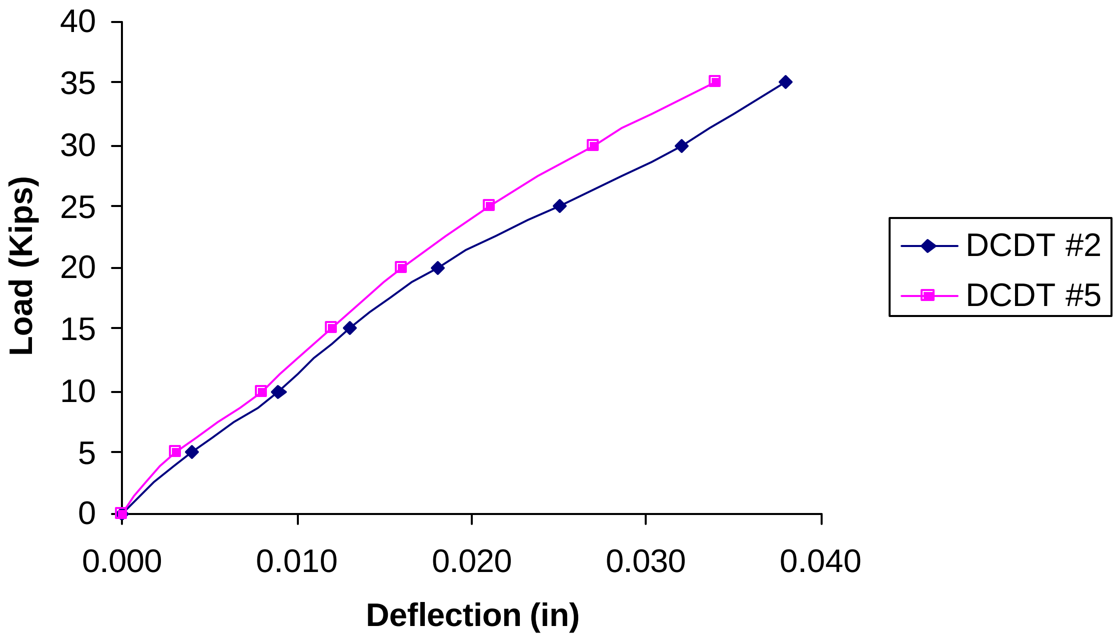

Figure B-74 Fatigue Specimen #1 Main Bar #2-3600K Cycles

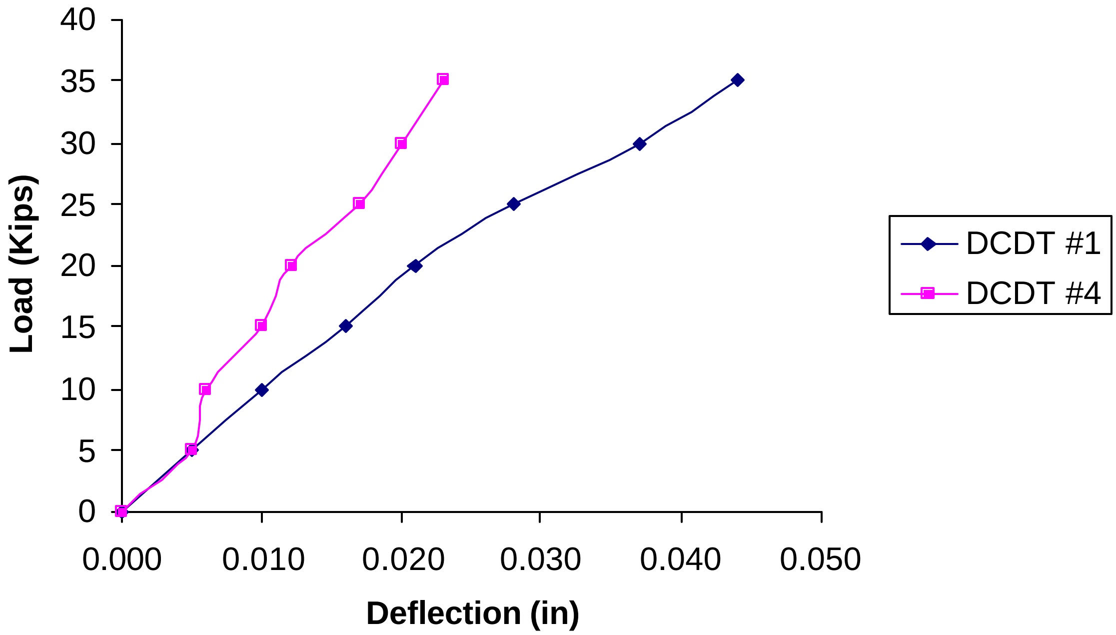

Figure B-75 Fatigue Specimen #1 Main Bar #3-3600K Cycles

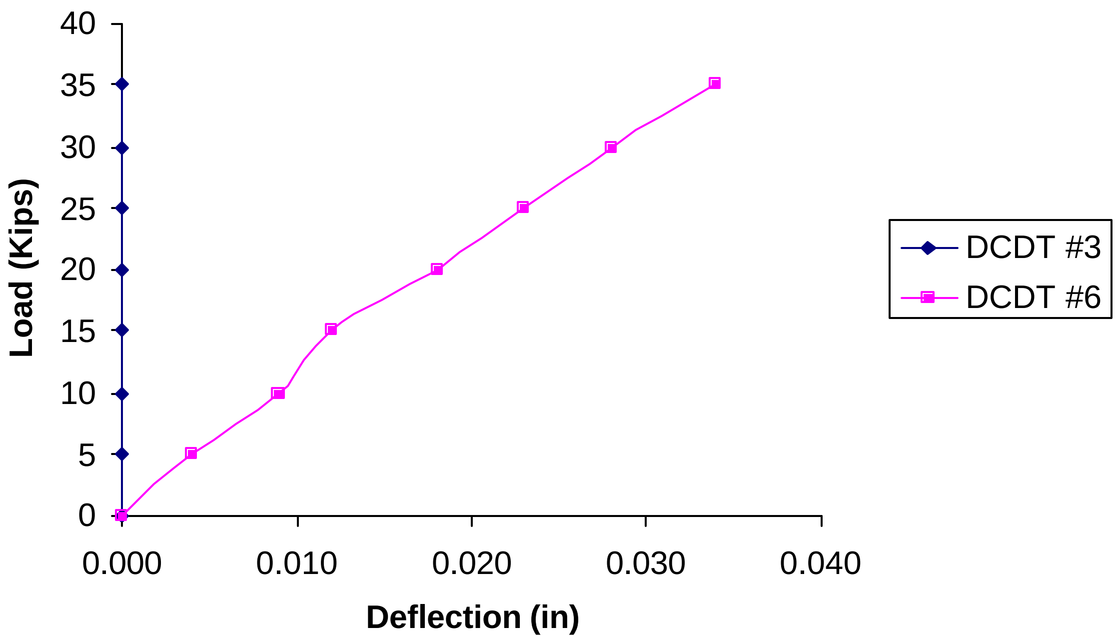

Figure B-76 Fatigue Specimen #1 Main Bar #1-3750K Cycles

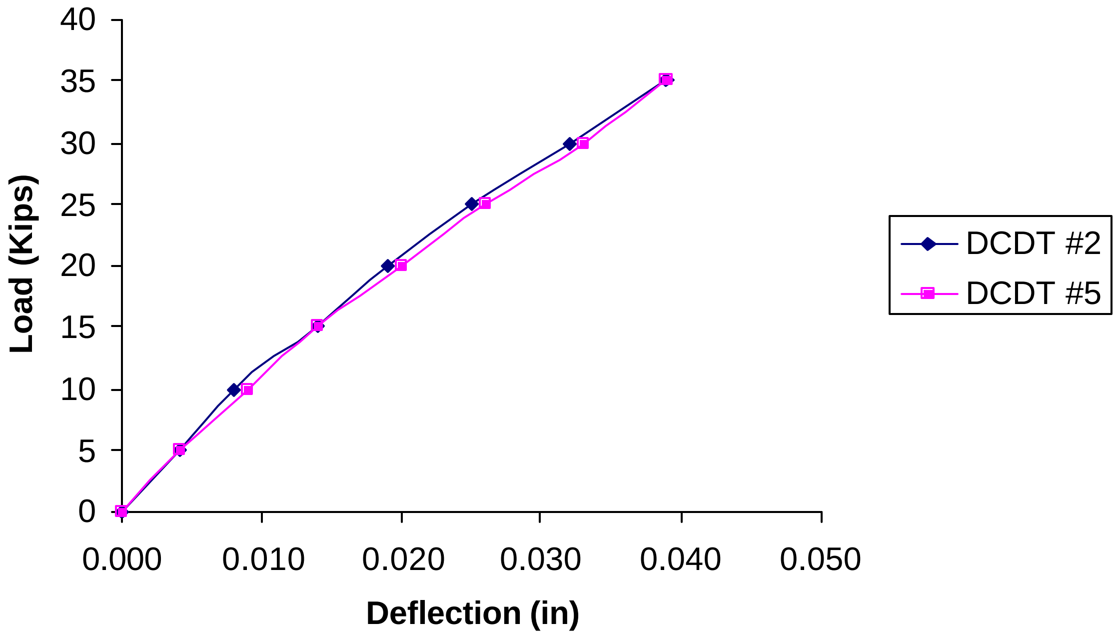

Figure B-77 Fatigue Specimen #1 Main Bar #2-3750K Cycles

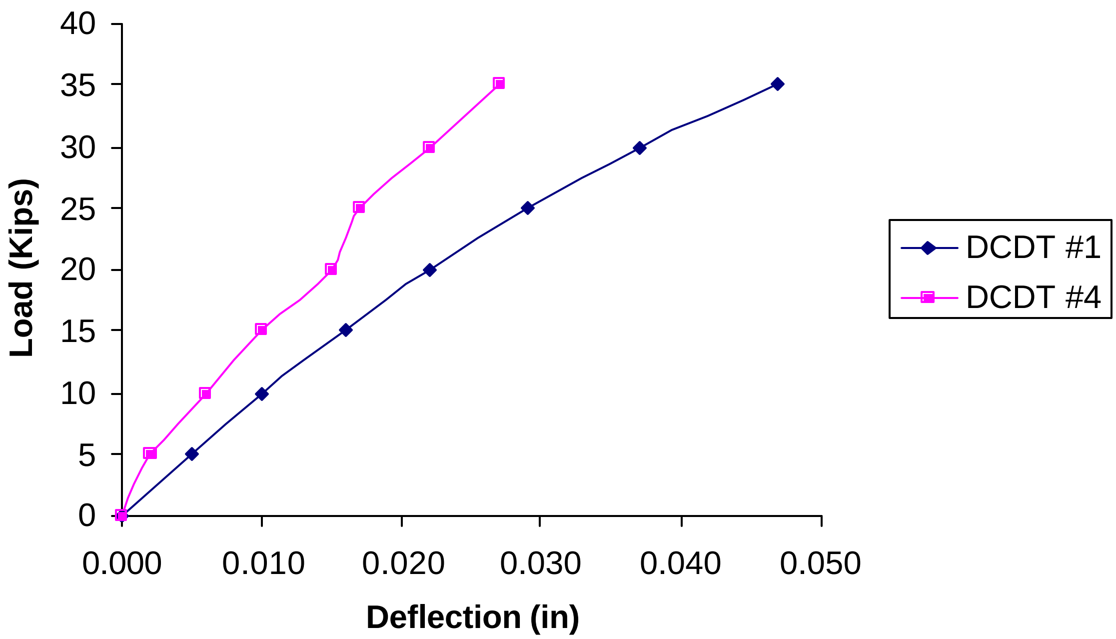

Figure B-78 Fatigue Specimen #1 Main Bar #3-3750K Cycles

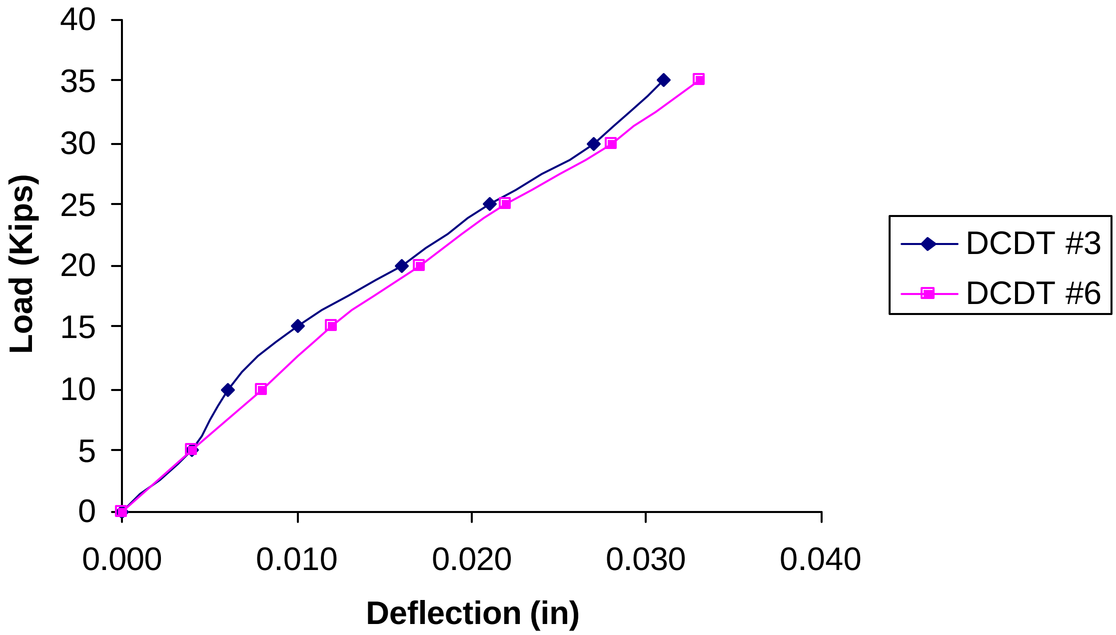

Figure B-79 Fatigue Specimen #1 Main Bar #1-3900K Cycles

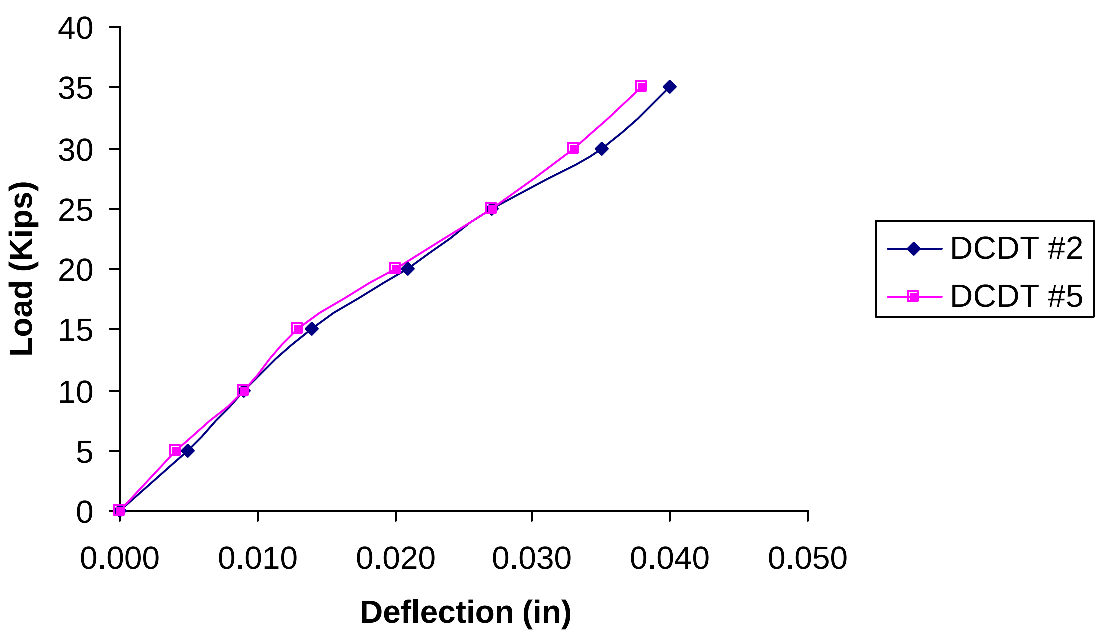

Figure B-80 Fatigue Specimen #1 Main Bar #2-3900K Cycles

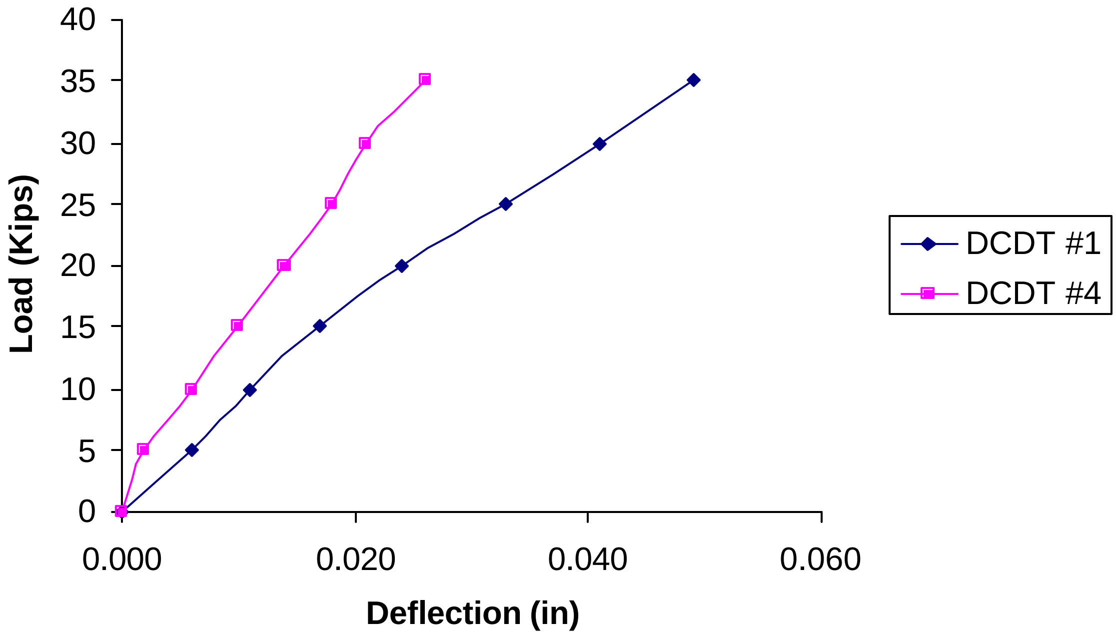

Figure B-81 Fatigue Specimen #1 Main Bar #3-3900K Cycles

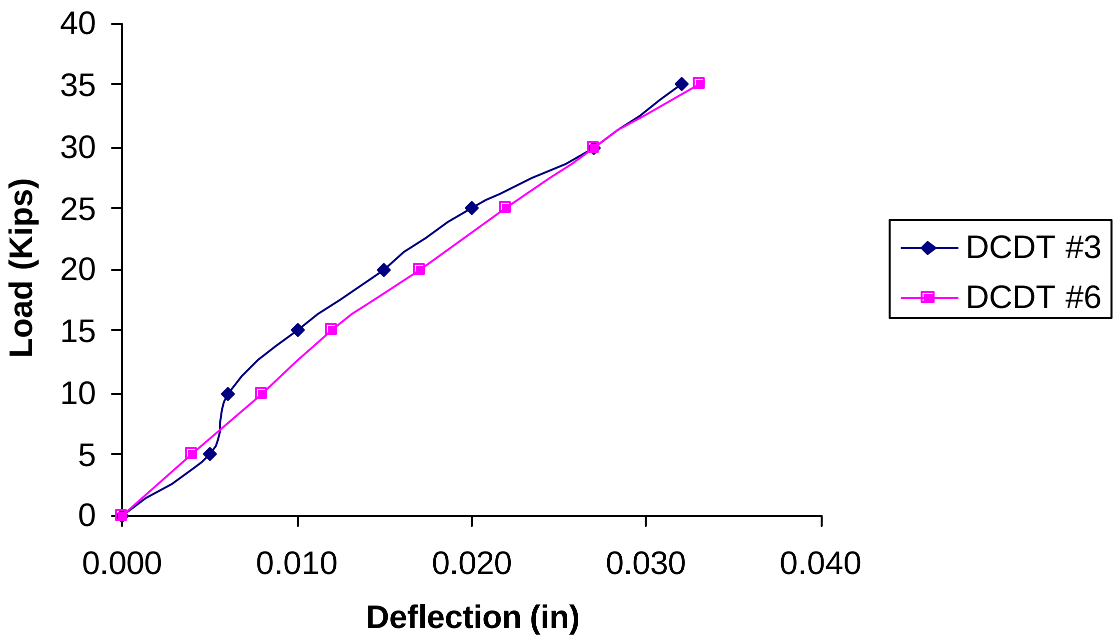

Figure B-82 Fatigue Specimen #1 Main Bar #1-4050K Cycles

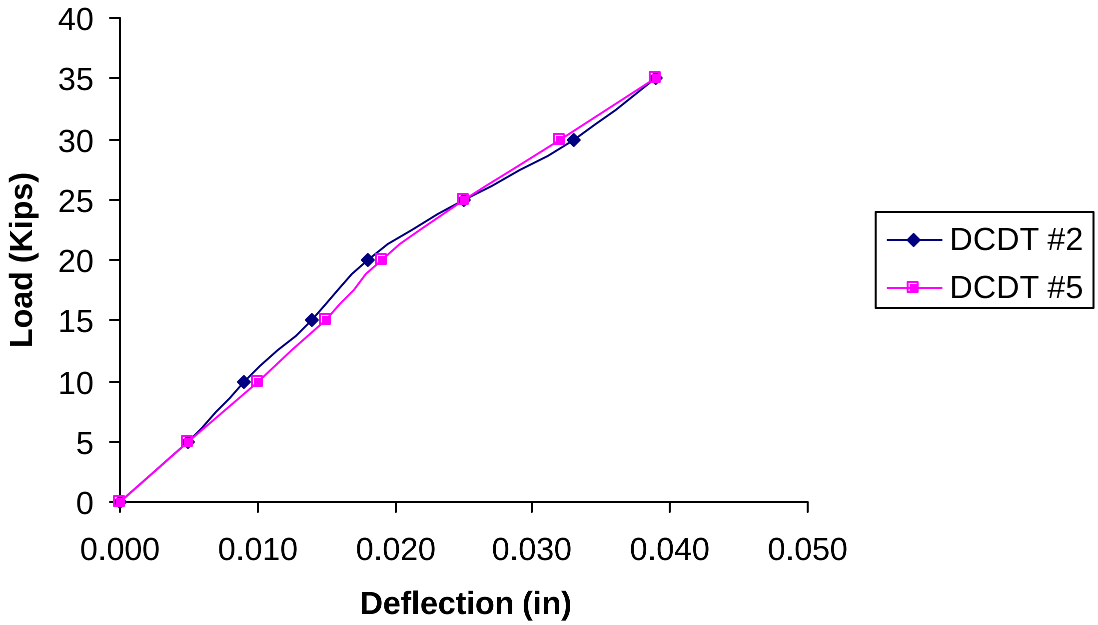

Figure B-83 Fatigue Specimen #1 Main Bar #2-4050K Cycles

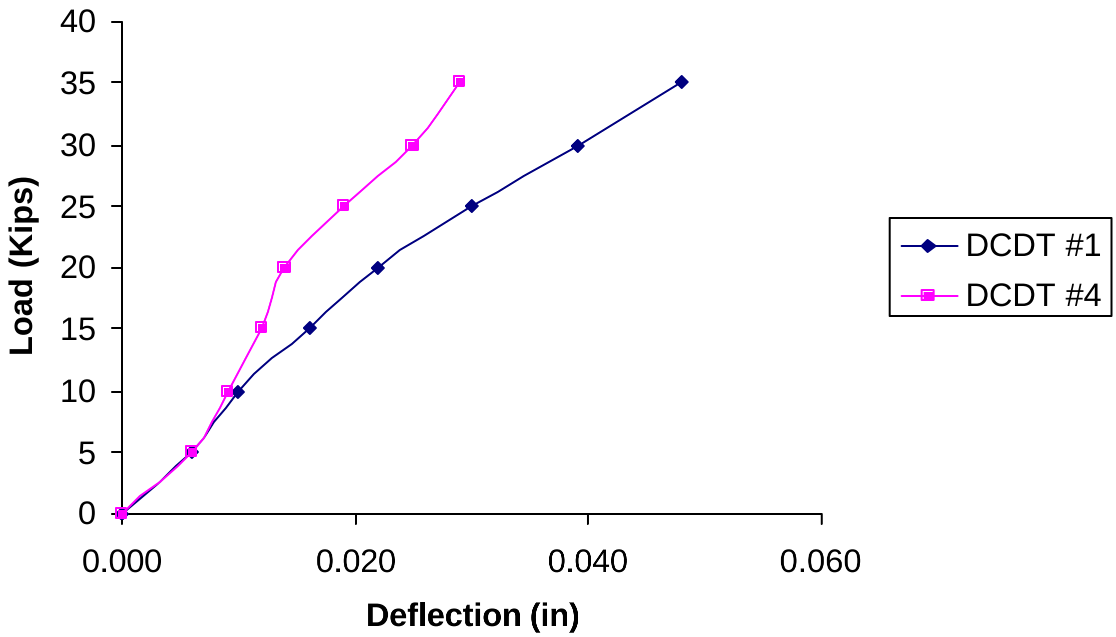

Figure B-84 Fatigue Specimen #1 Main Bar #3-4050K Cycles

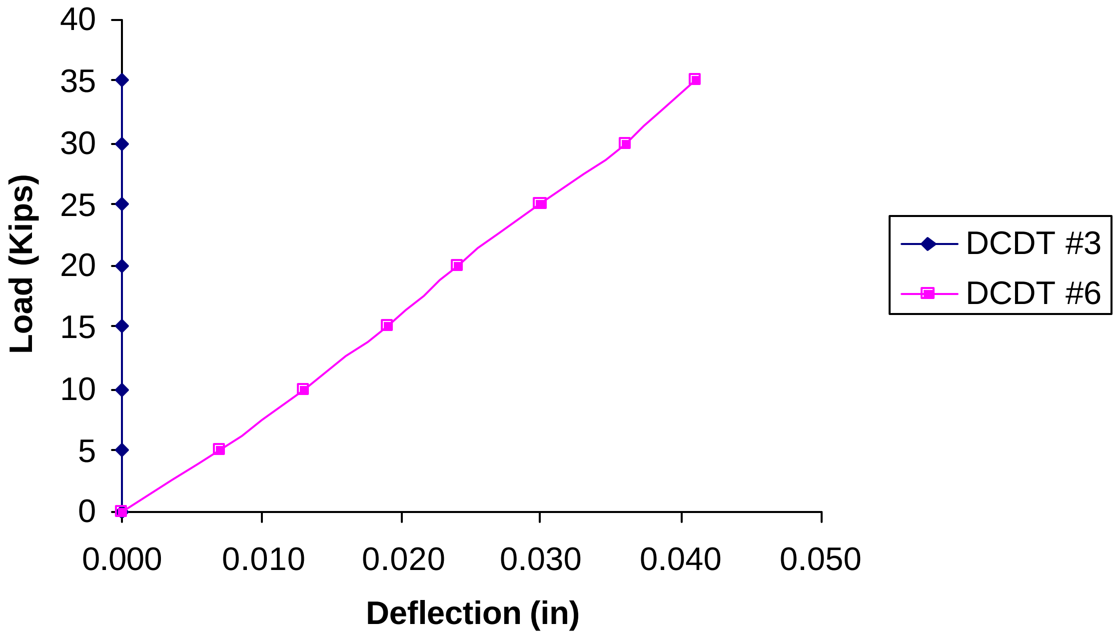

Figure B-85 Fatigue Specimen #1 Main Bar #1-4200K Cycles

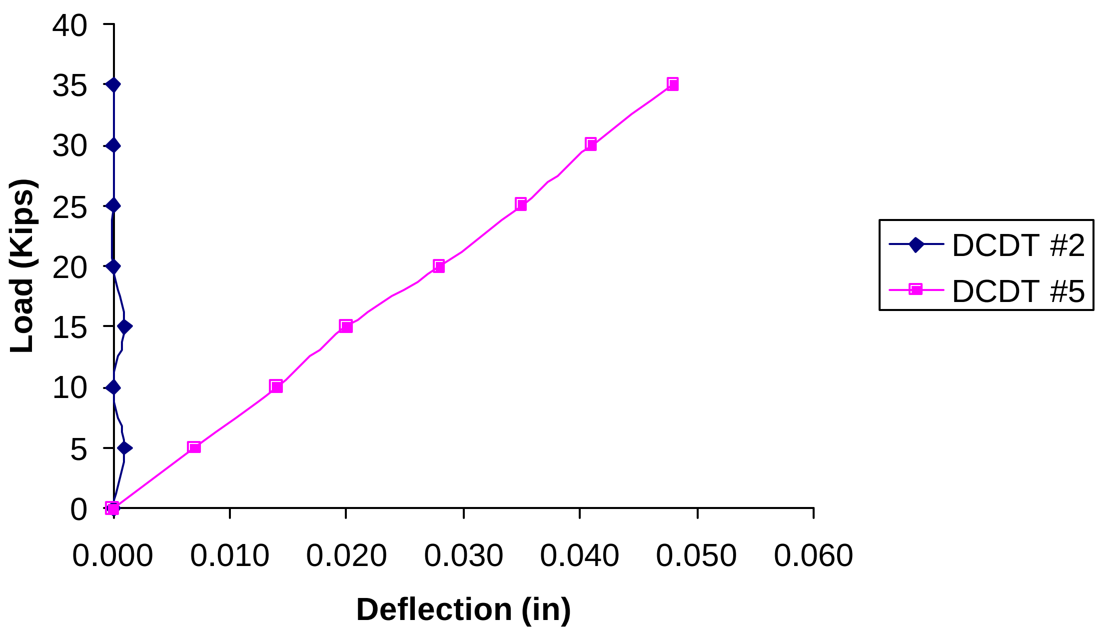

Figure B-86 Fatigue Specimen #1 Main Bar #2-4200K Cycles

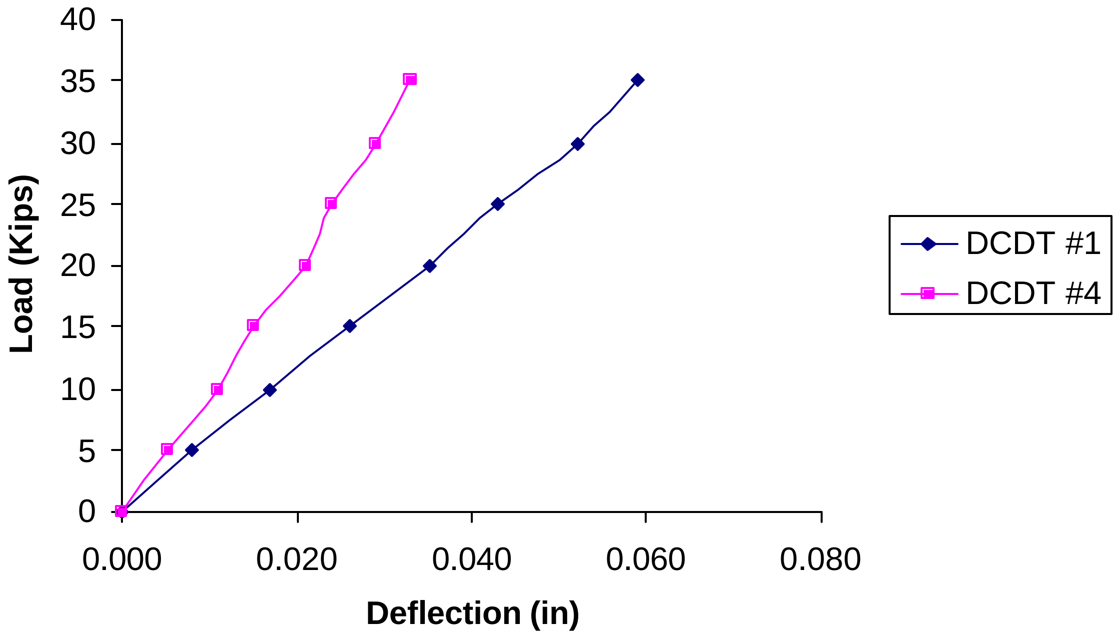

Figure B-87 Fatigue Specimen #1 Main Bar #3-4200K Cycles

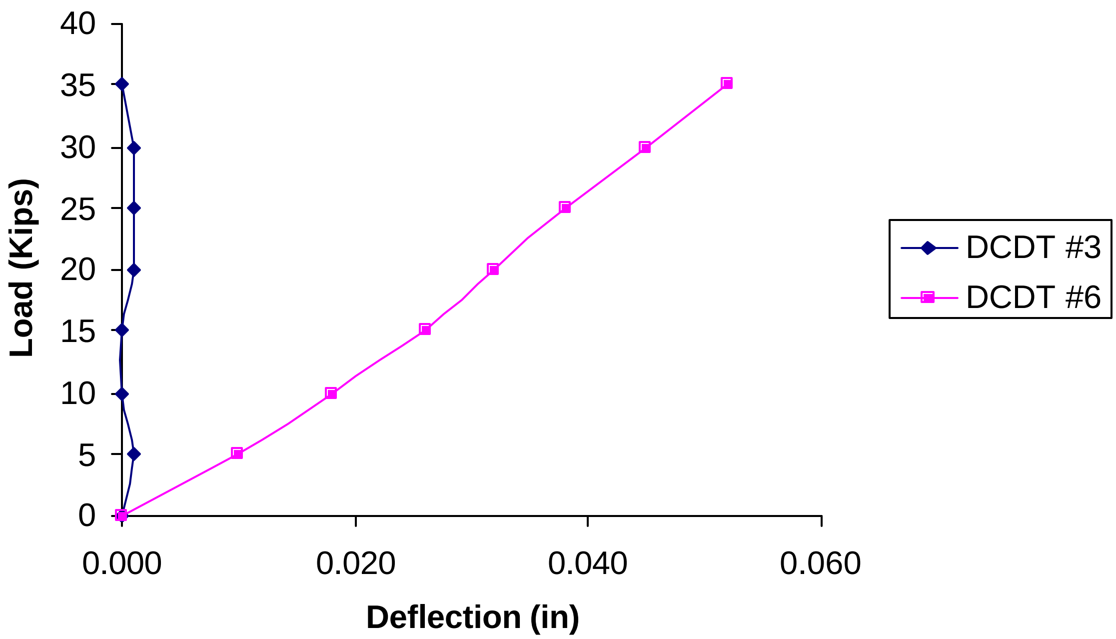

Figure B-88 Fatigue Specimen #1 Main Bar #1-4350K Cycles

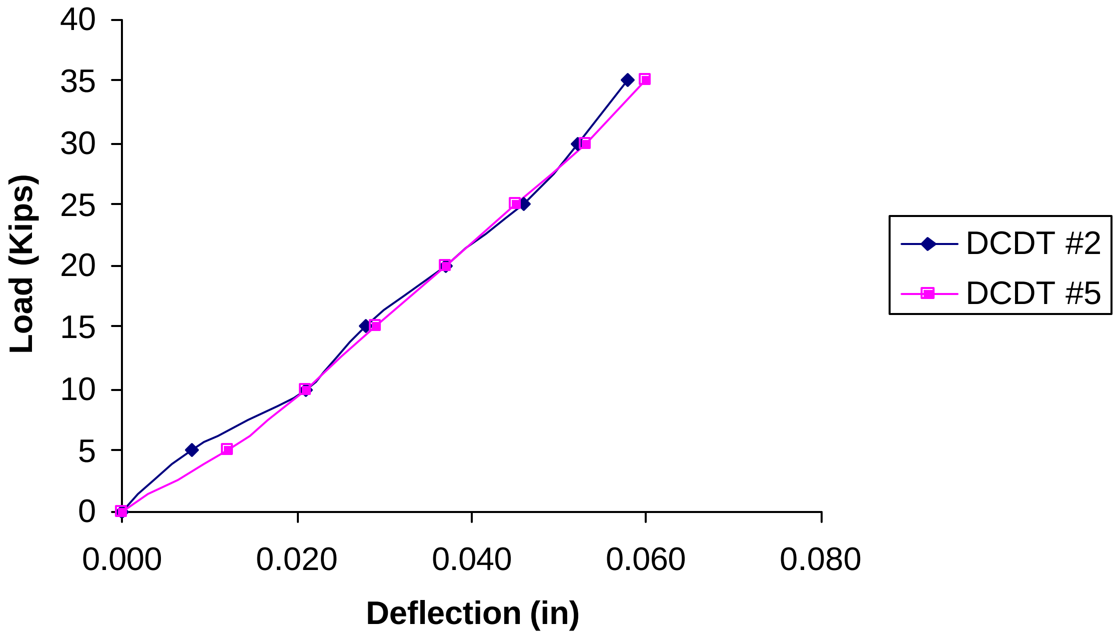

Figure B-89 Fatigue Specimen #1 Main Bar #2-4350K Cycles

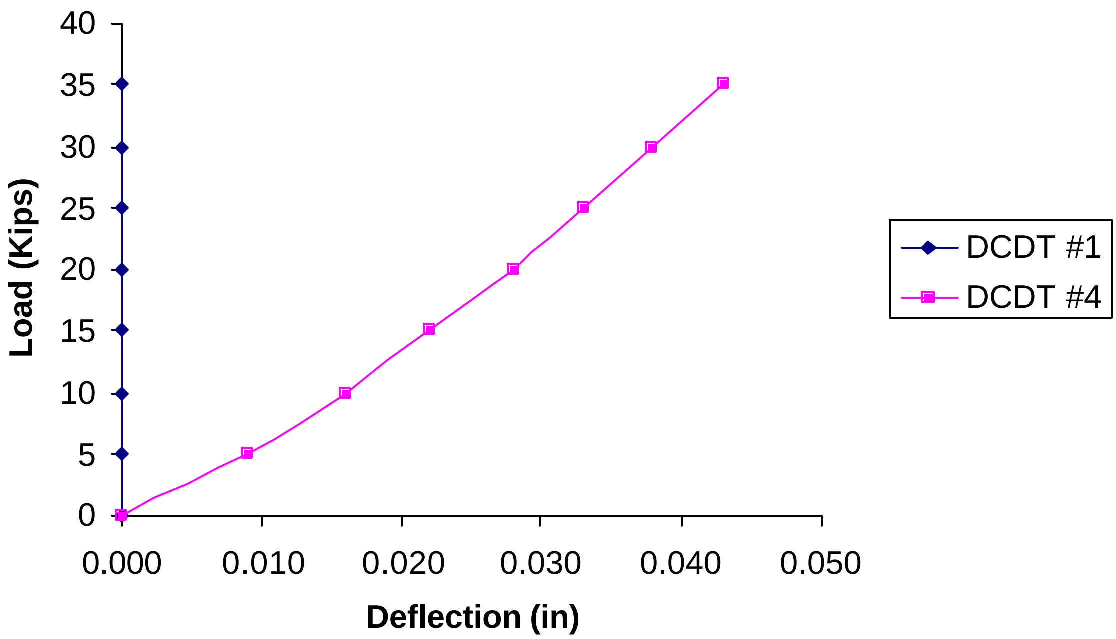

Figure B-90 Fatigue Specimen #1 Main Bar #3-4350K Cycles

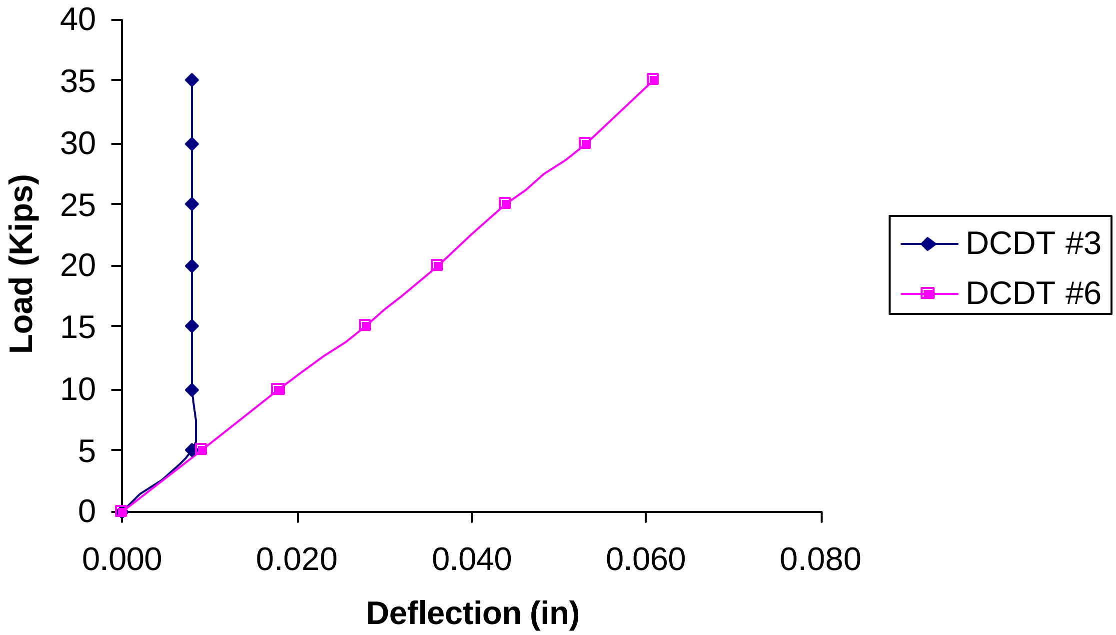

Figure B-91 Fatigue Specimen #1 Main Bar #1-4400K Cycles

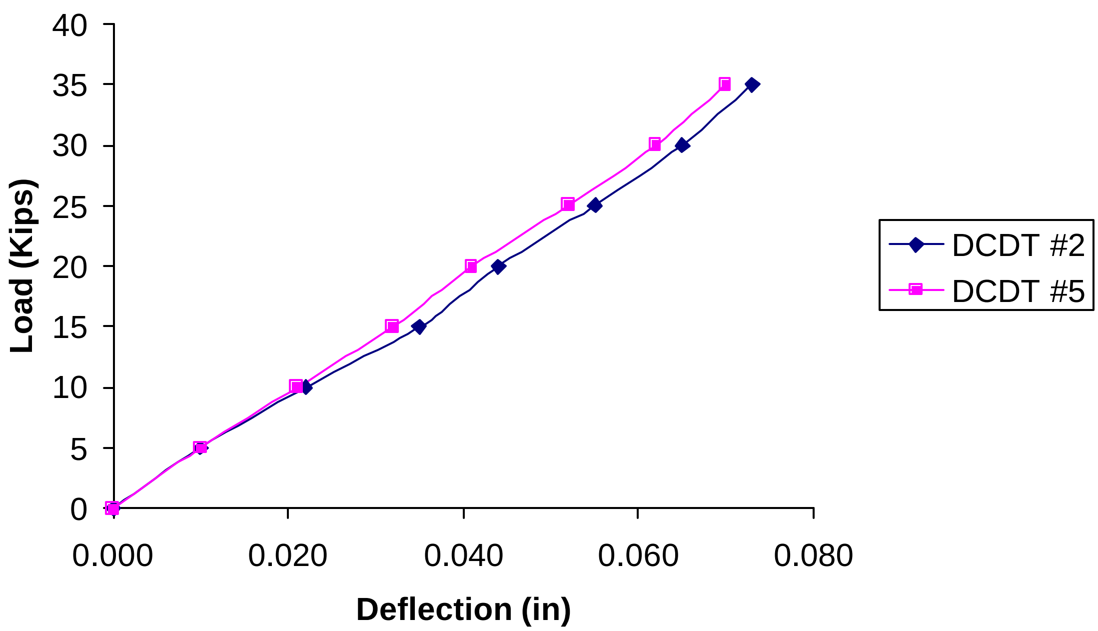

Figure B-92 Fatigue Specimen #1 Main Bar #2-4400K Cycles

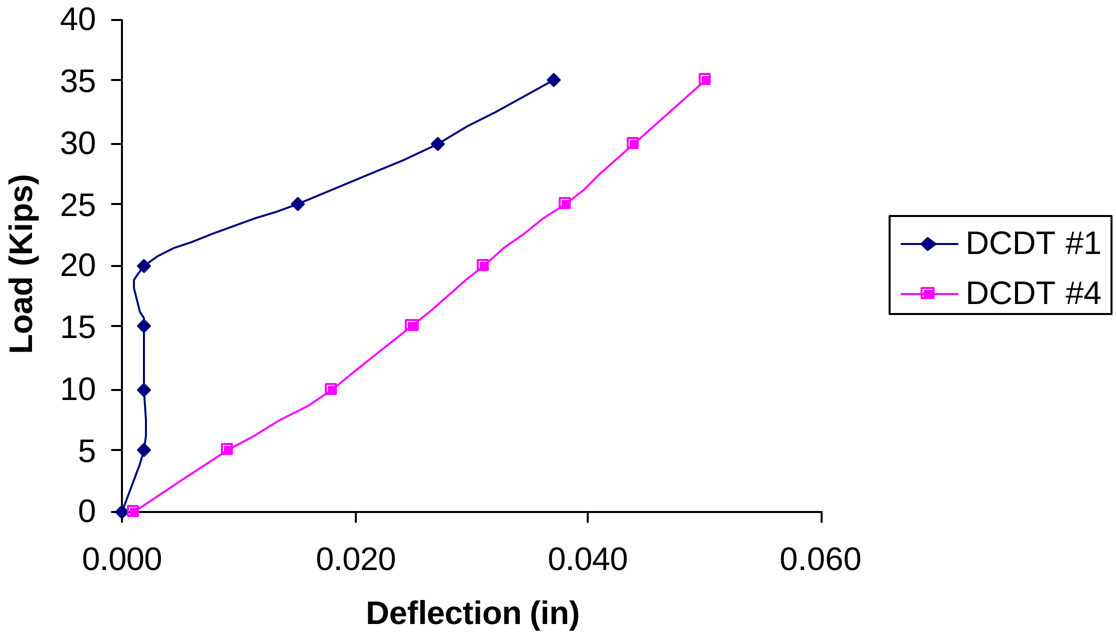

Figure B-93 Fatigue Specimen #1 Main Bar #3-4400K Cycles

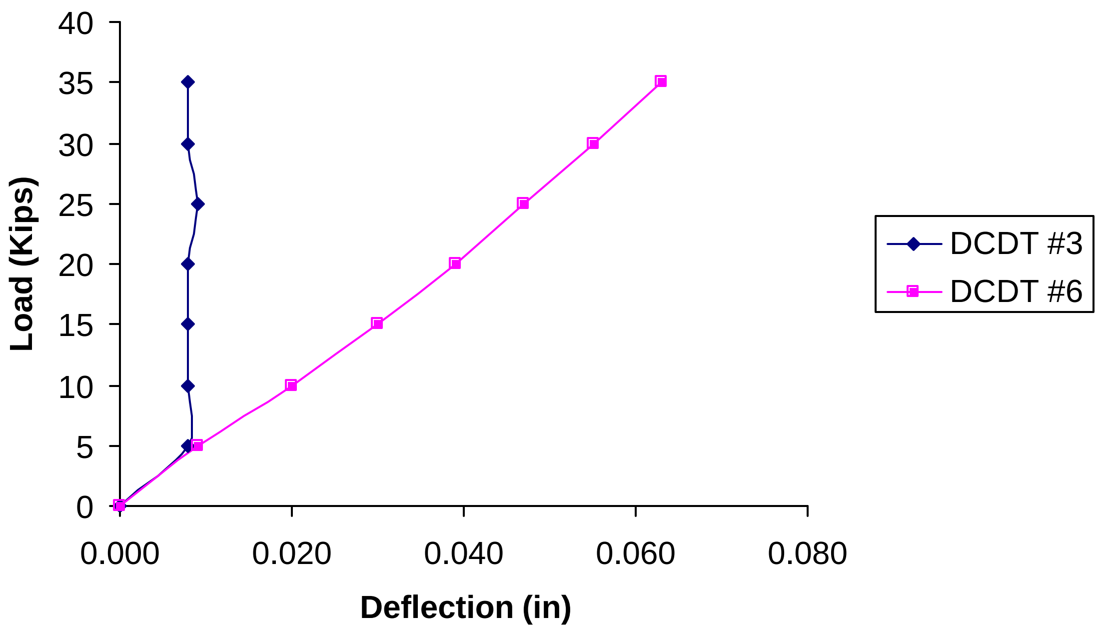

Figure B-94 Fatigue Specimen #1 Main Bar #1-4550K Cycles

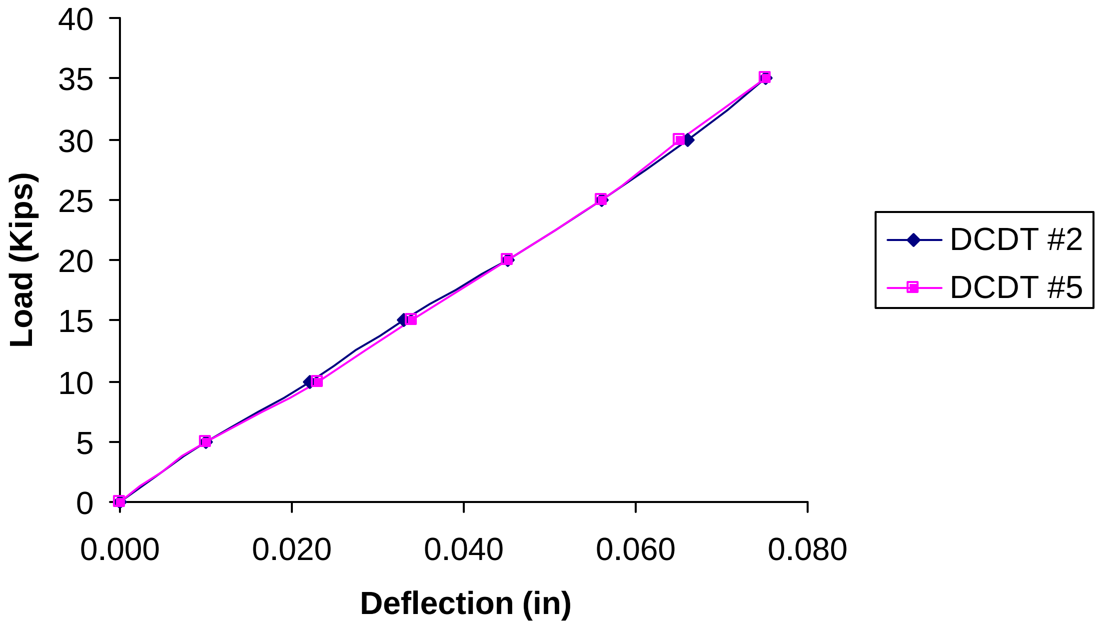

Figure B-95 Fatigue Specimen #1 Main Bar #2-4550K Cycles

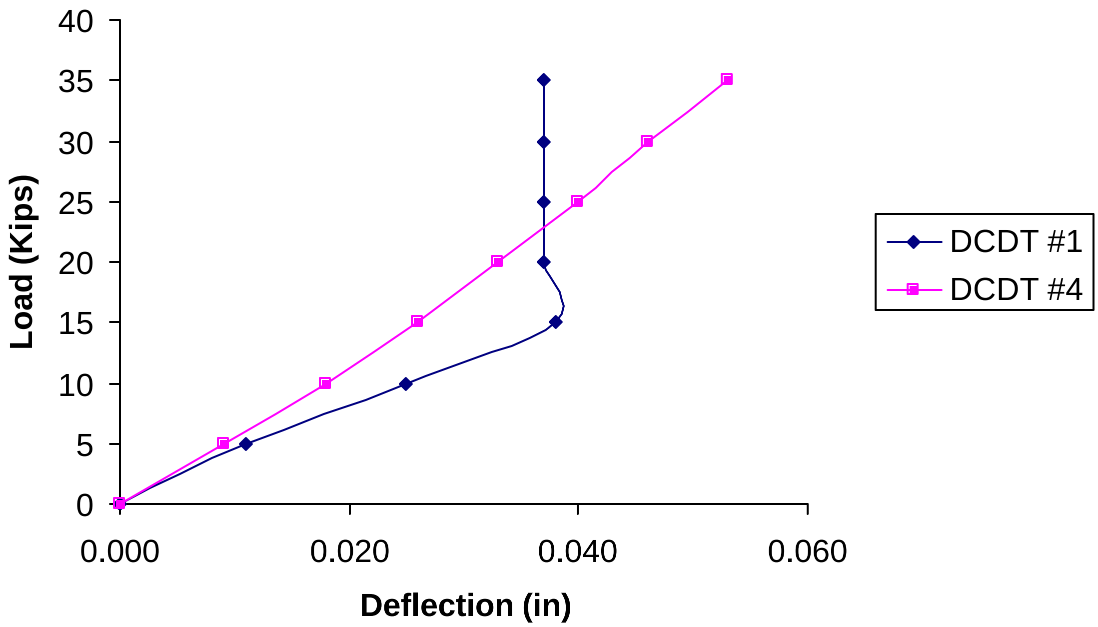

Figure B-96 Fatigue Specimen #1 Main Bar #3-4550K Cycles

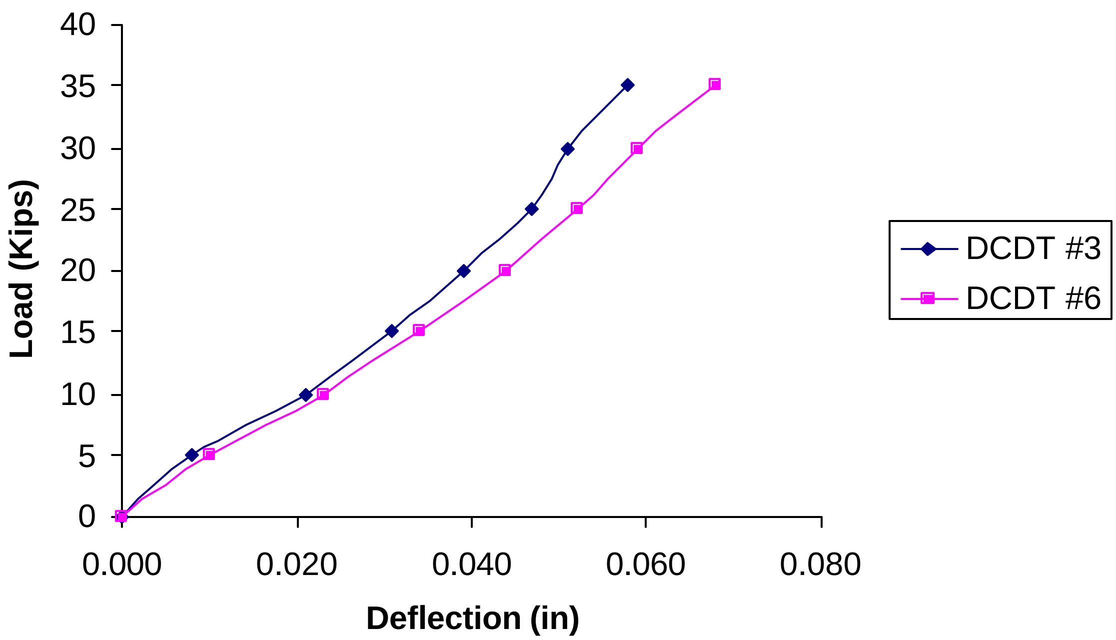

Figure B-97 Fatigue Specimen #1 Main Bar #1-4700K Cycles

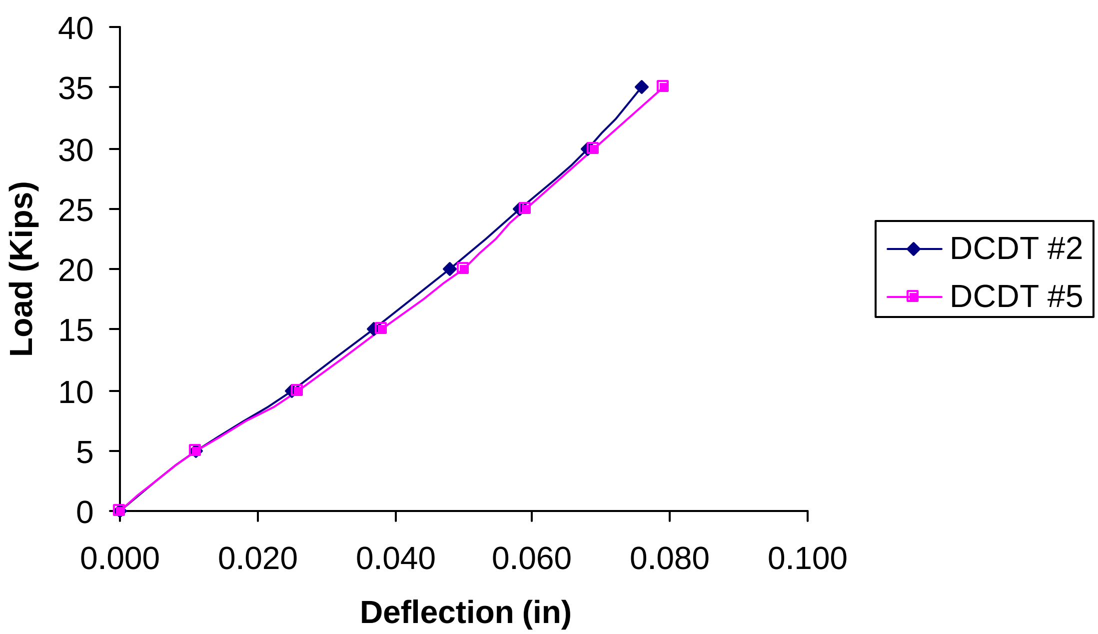

Figure B-98 Fatigue Specimen #1 Main Bar #2-4700K Cycles

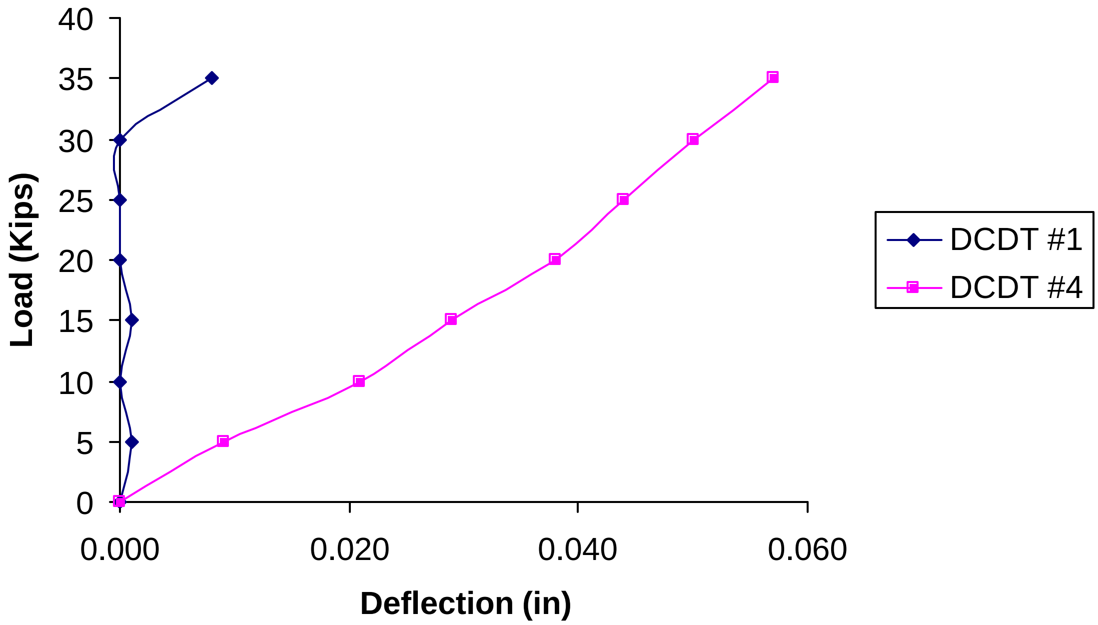

Figure B-99 Fatigue Specimen #1 Main Bar #3-4700K Cycles

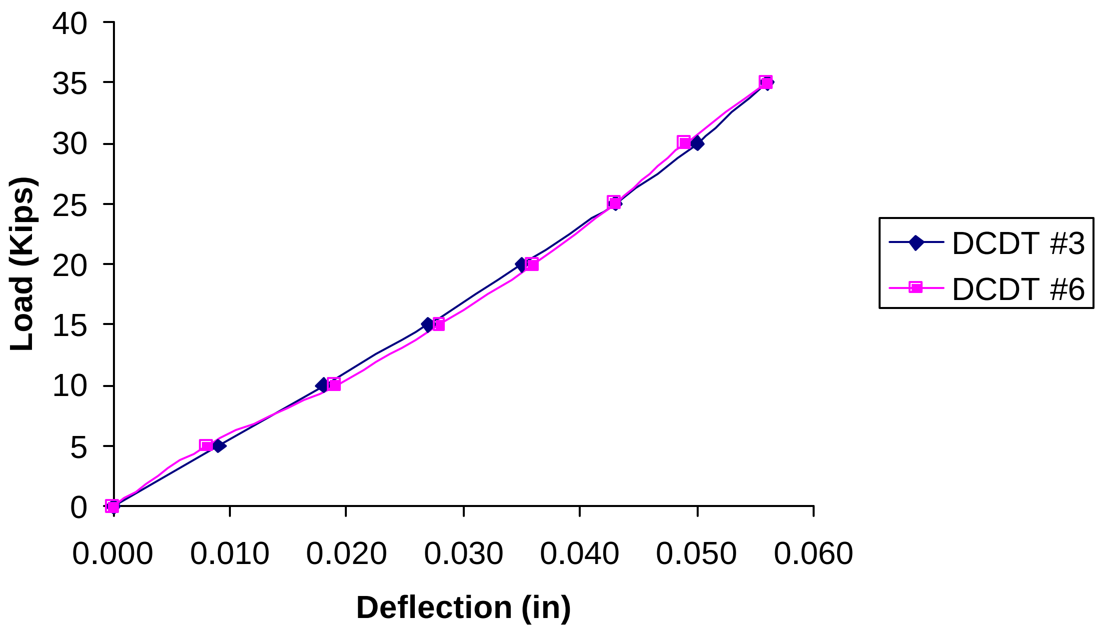

Figure B-100 Fatigue Specimen #1 Main Bar #1-4850K Cycles

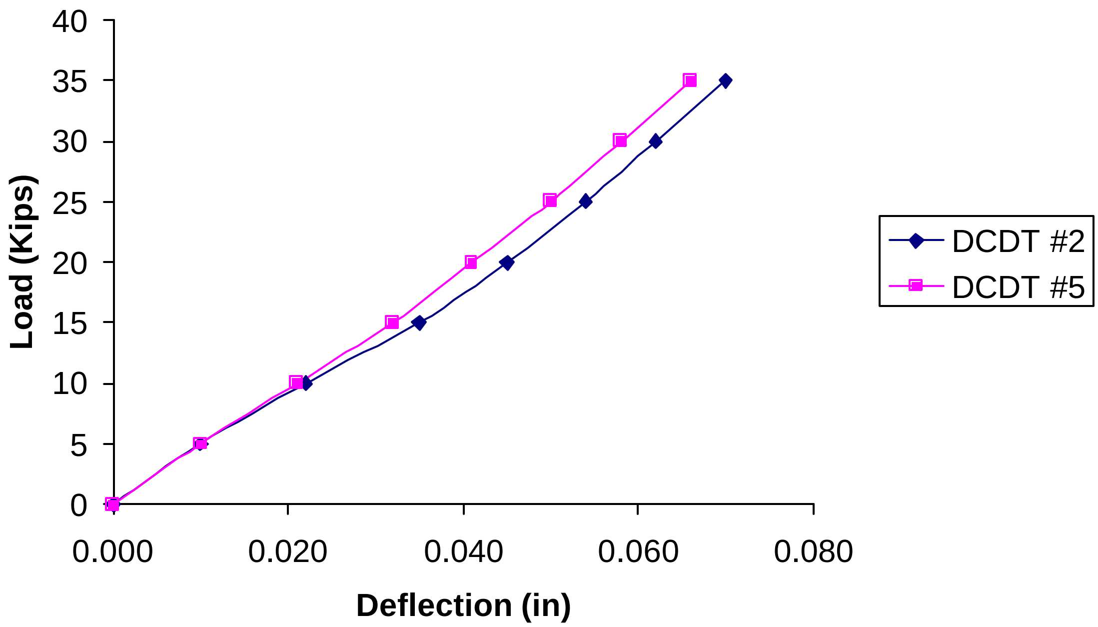

Figure B-101 Fatigue Specimen #1 Main Bar #2-4850K Cycles

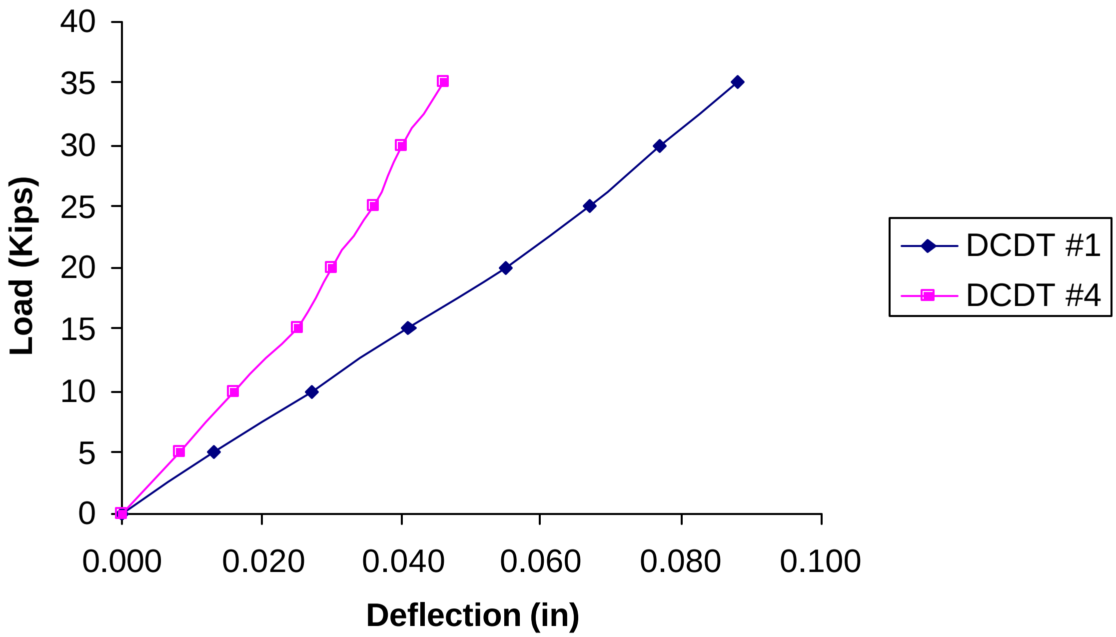

Figure B-102 Fatigue Specimen #1 Main Bar #3-4850K Cycles

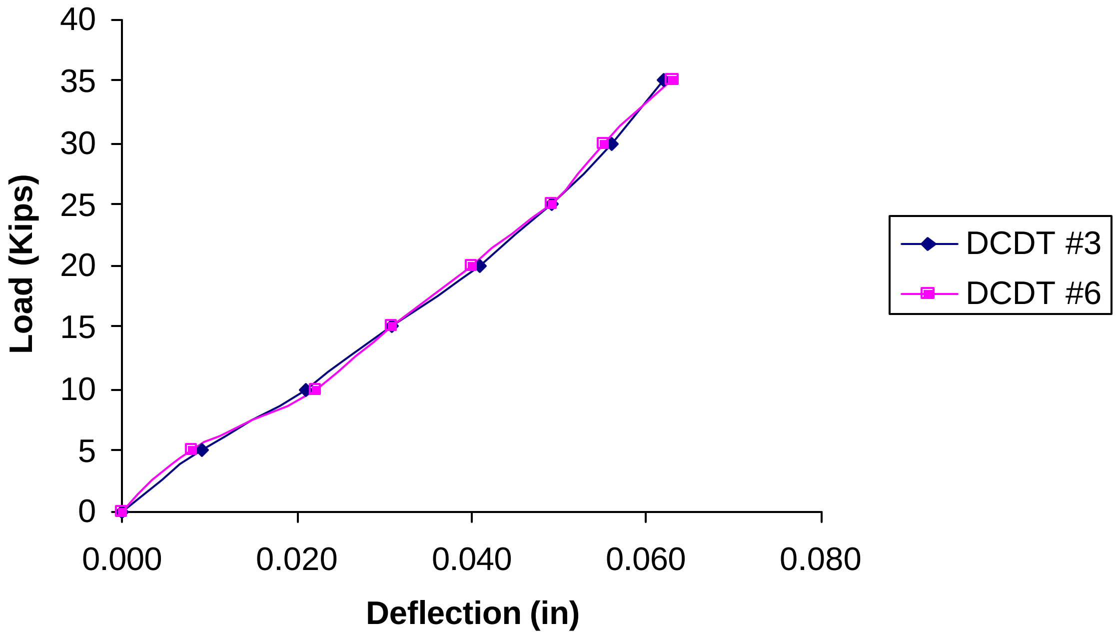

Figure B-103 Fatigue Specimen #1 Main Bar #1-5000K Cycles

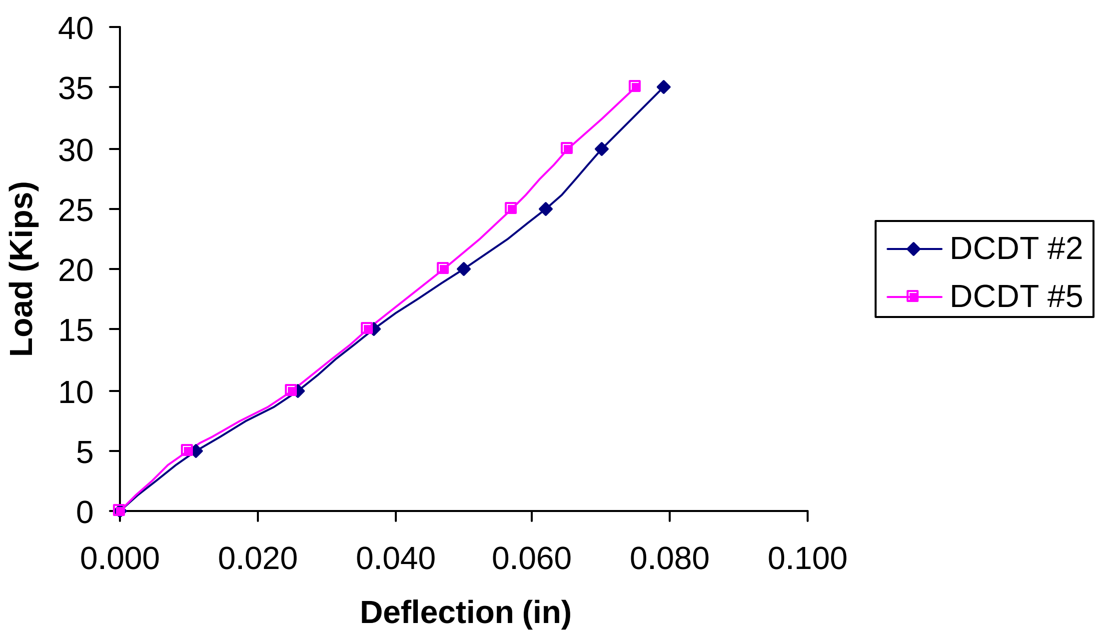

Figure B-104 Fatigue Specimen #1 Main Bar #2-5000K Cycles

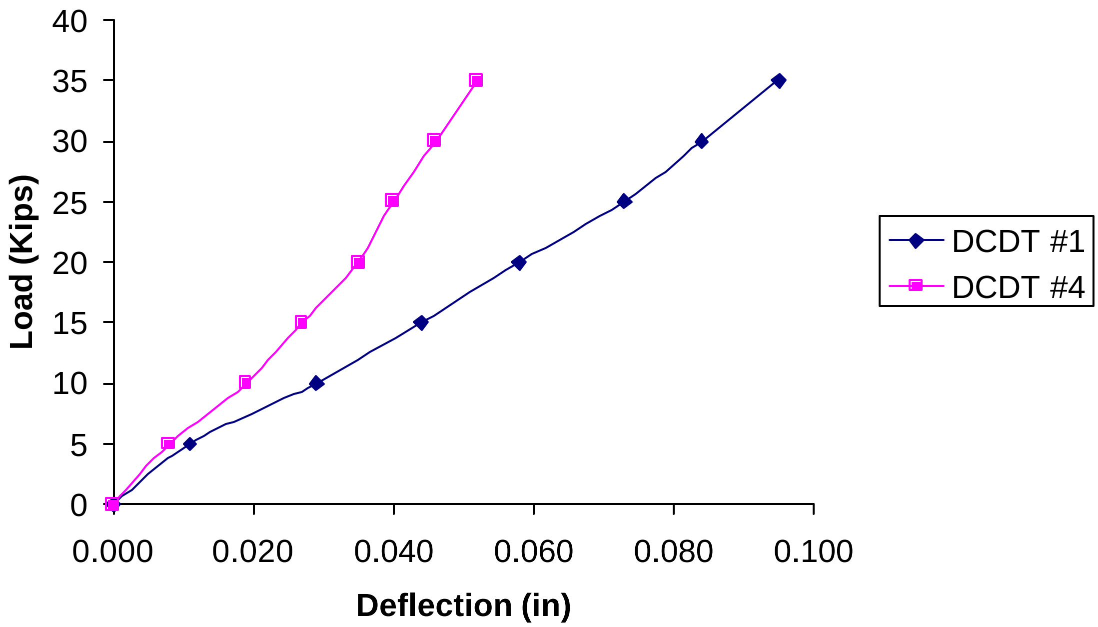

Figure B-105 Fatigue Specimen #1 Main Bar #3-5000K Cycles

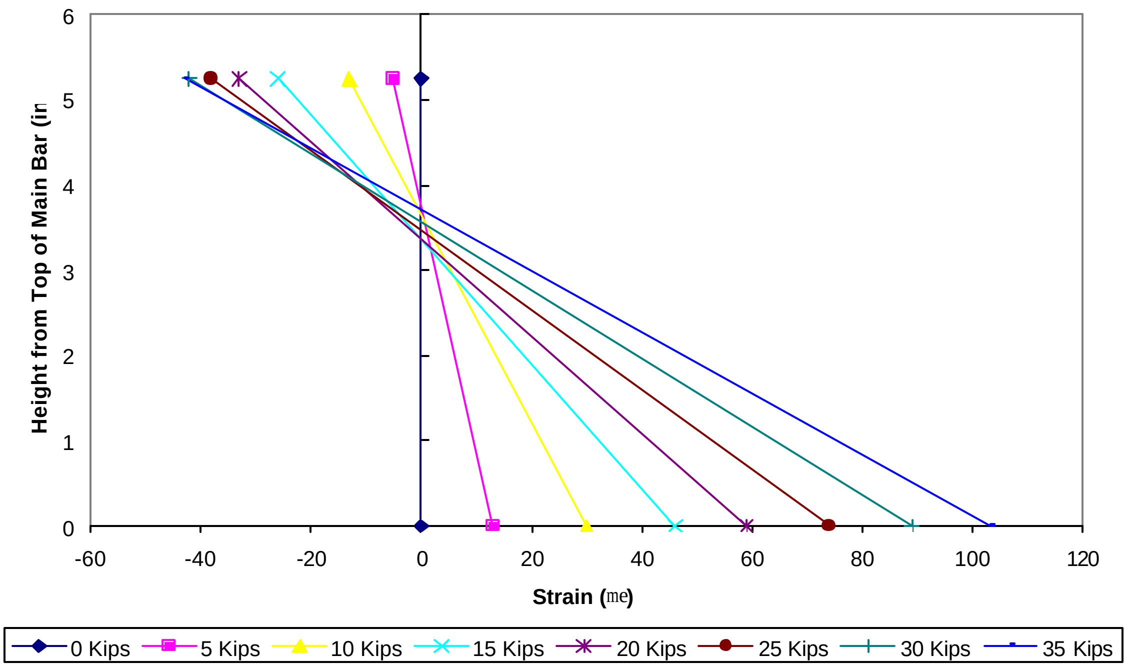

Figure B-106 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-Benchmark

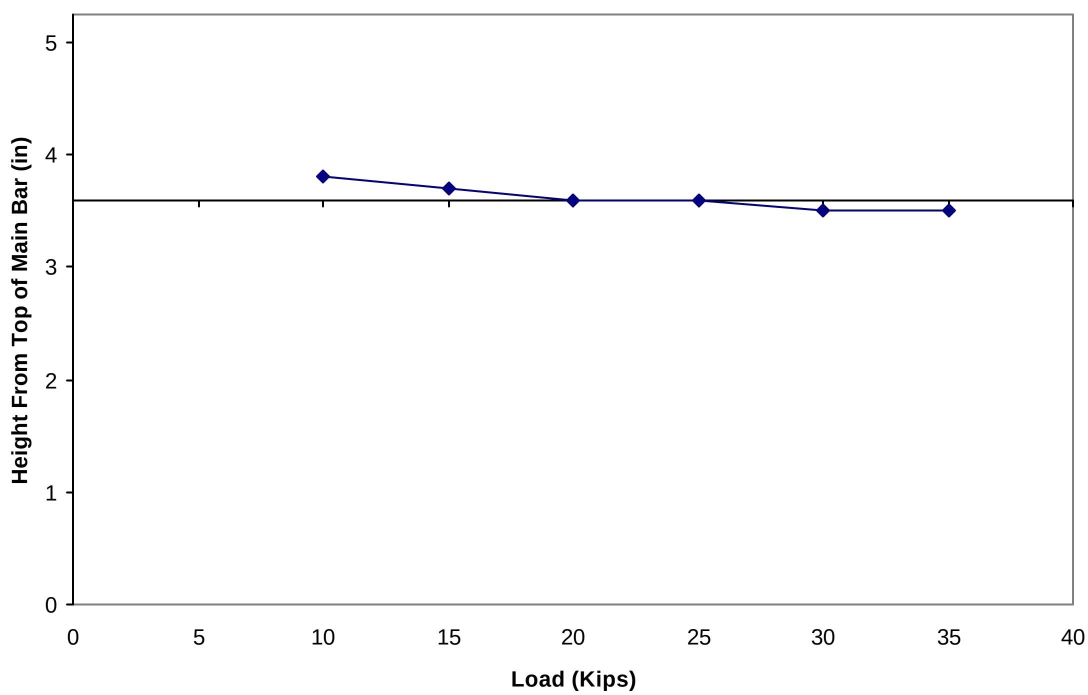

Figure B-107 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-Benchmark

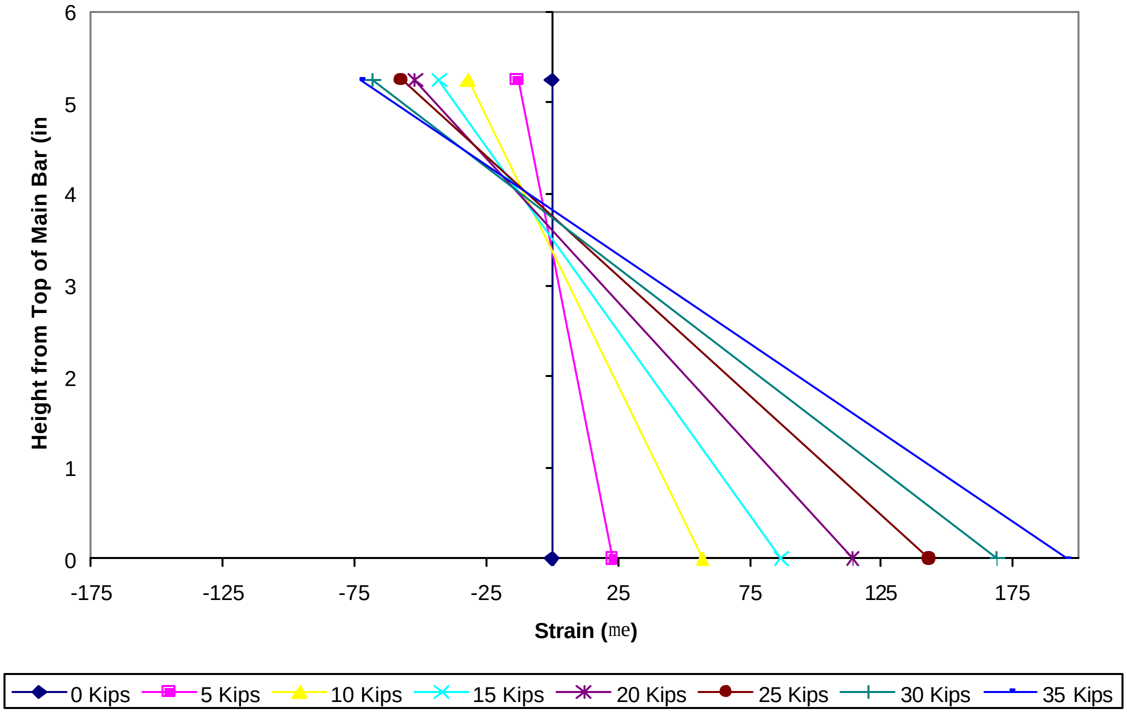

Figure B-108 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-Benchmark

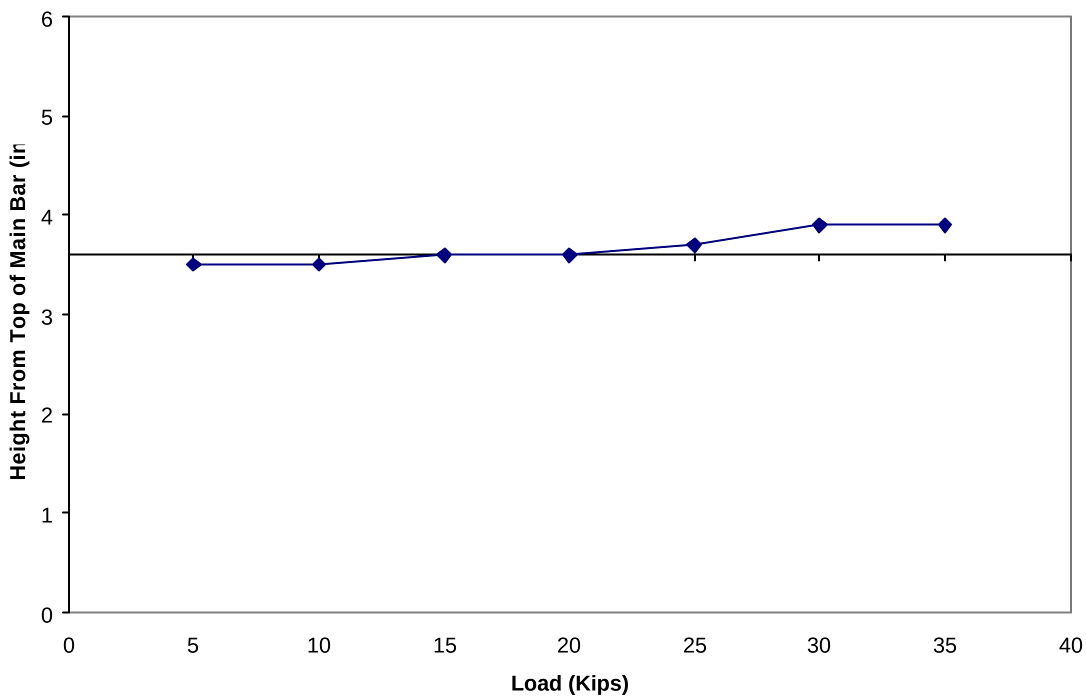

Figure B-109 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-Benchmark

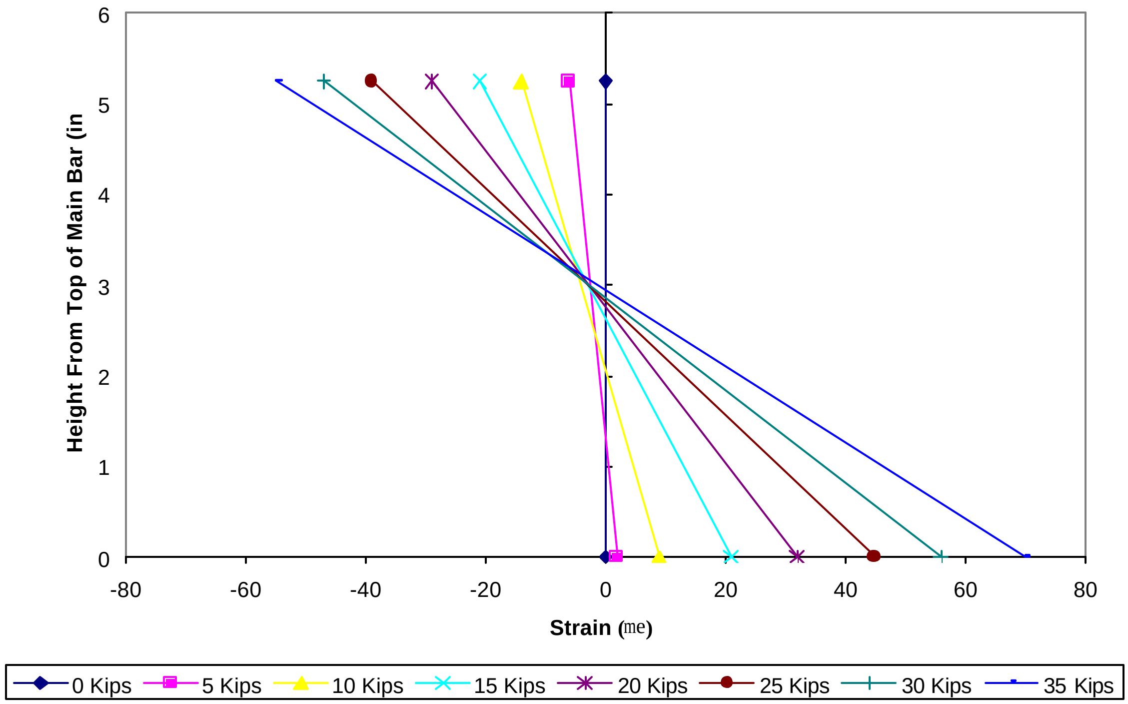

Figure B-110 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-150K Cycles

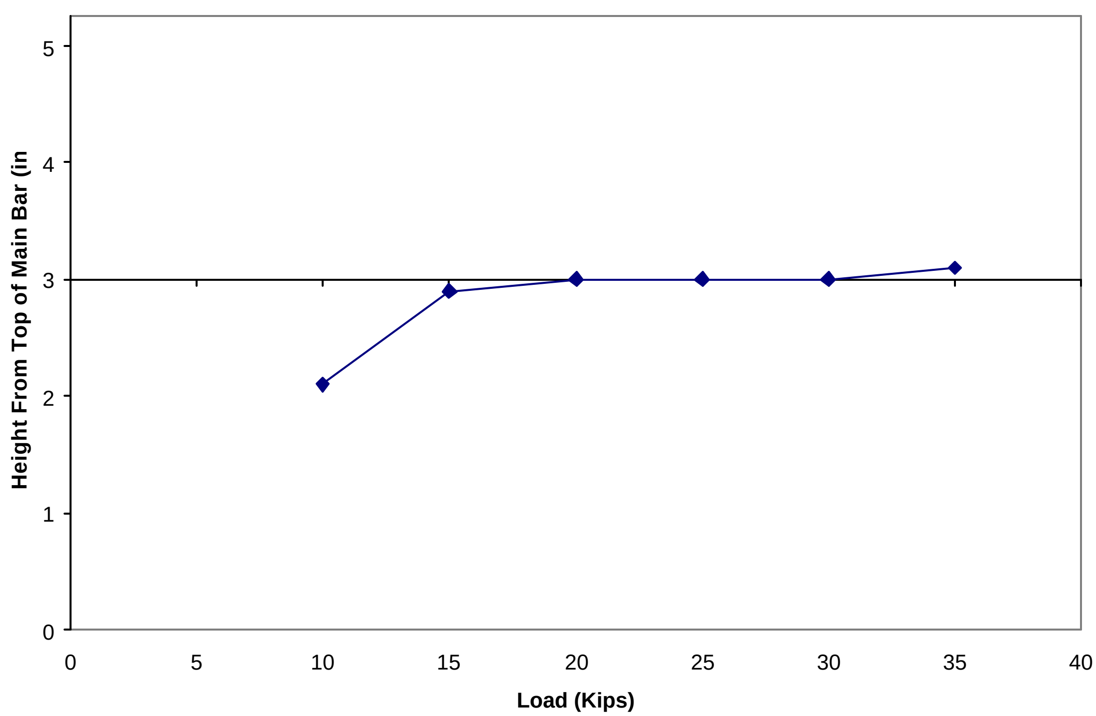

Figure B-111 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-150K Cycles

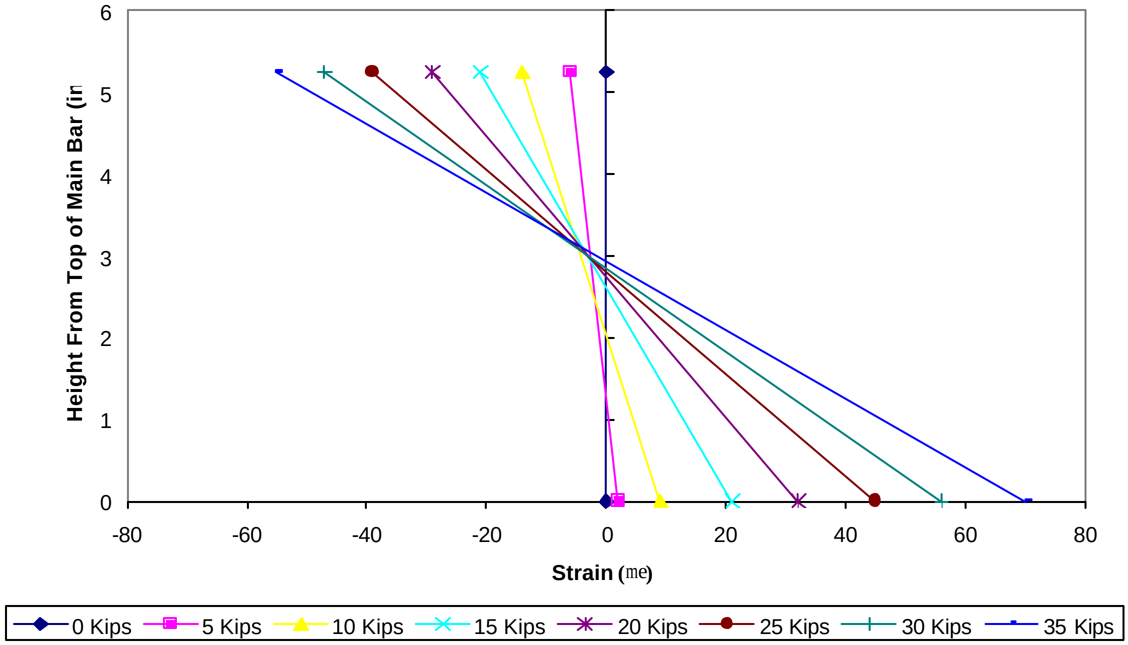

Figure B-112 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-150K Cycles

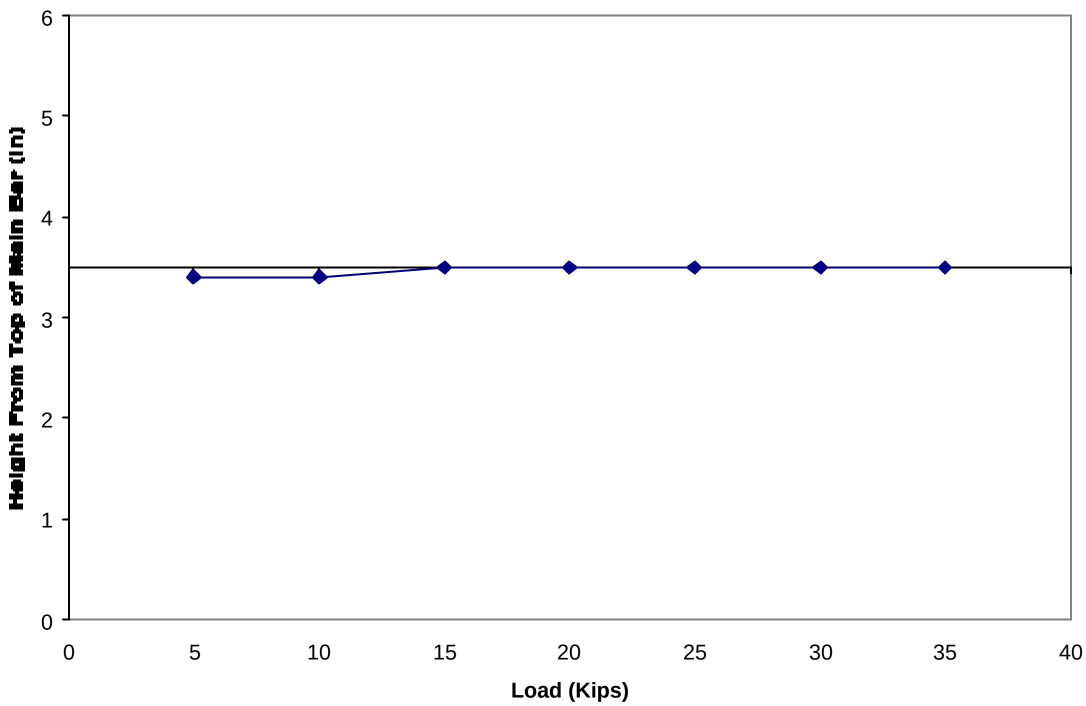

Figure B-113 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-150K Cycles

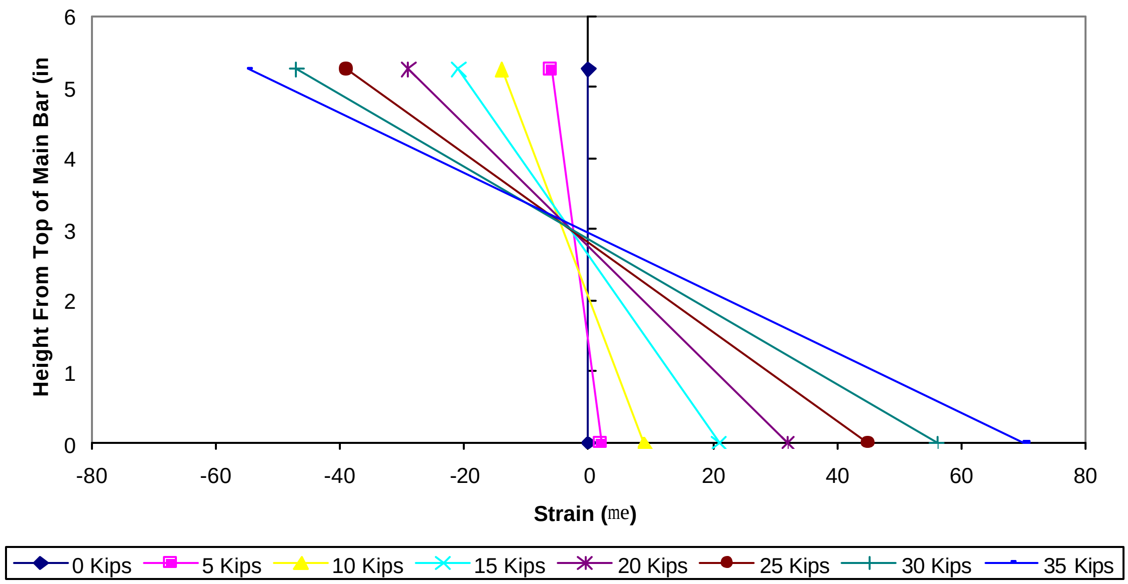

Figure B-114 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-300K Cycles

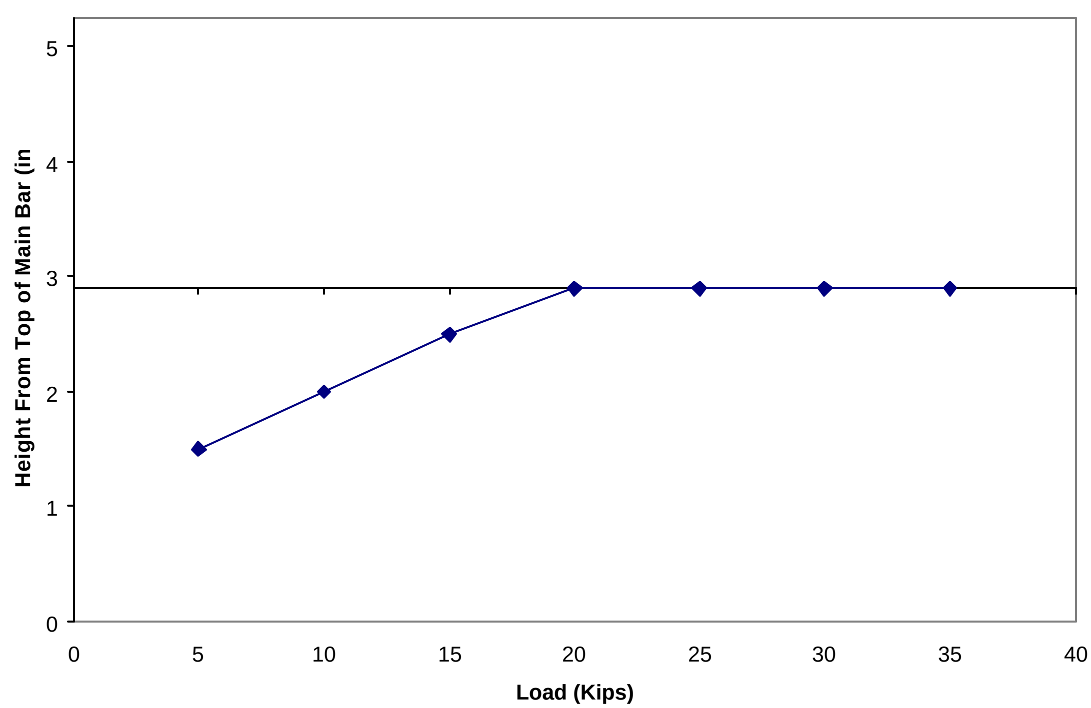

Figure B-115 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-300K Cycles

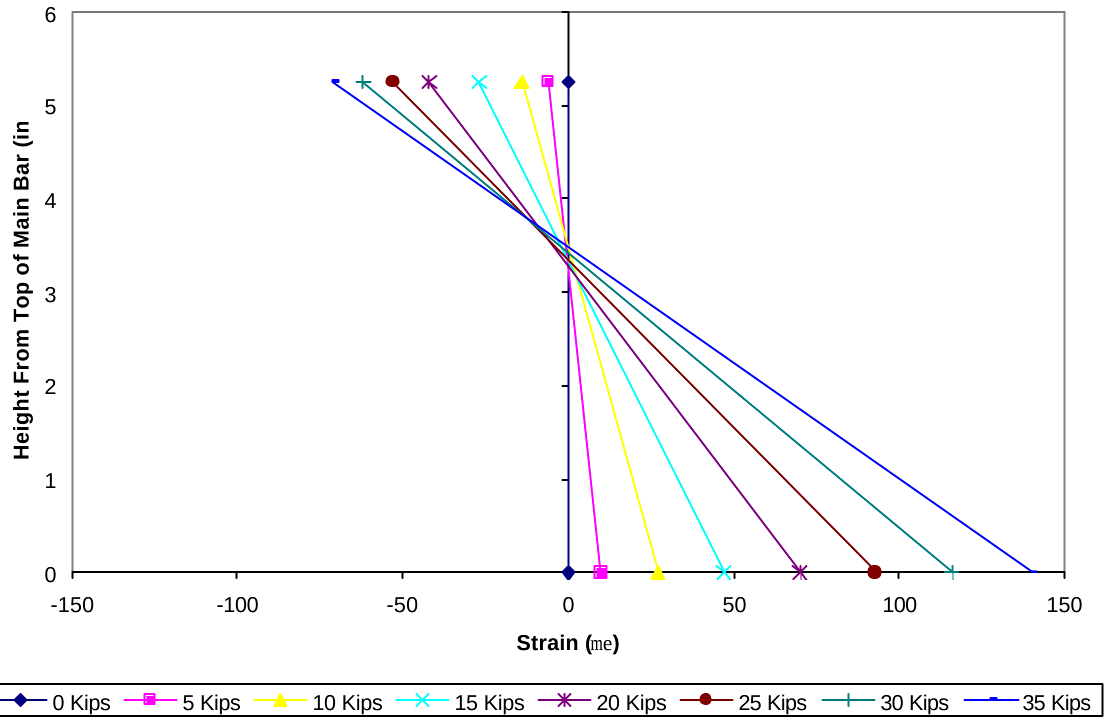

Figure B-116 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-300K Cycles

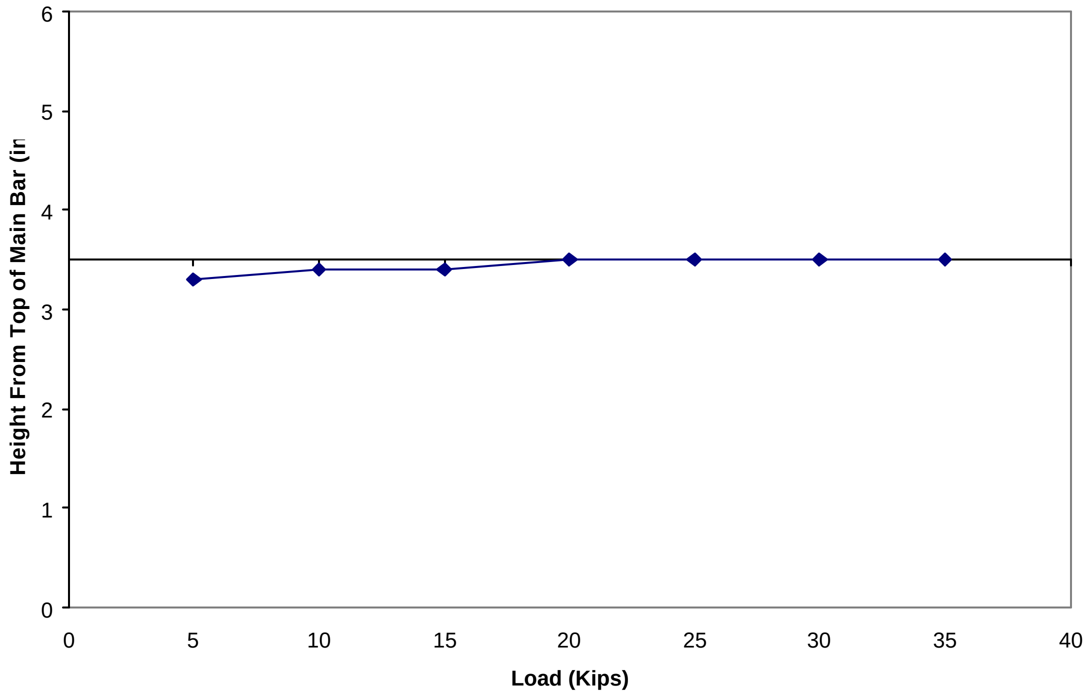

Figure B-117 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-300K Cycles

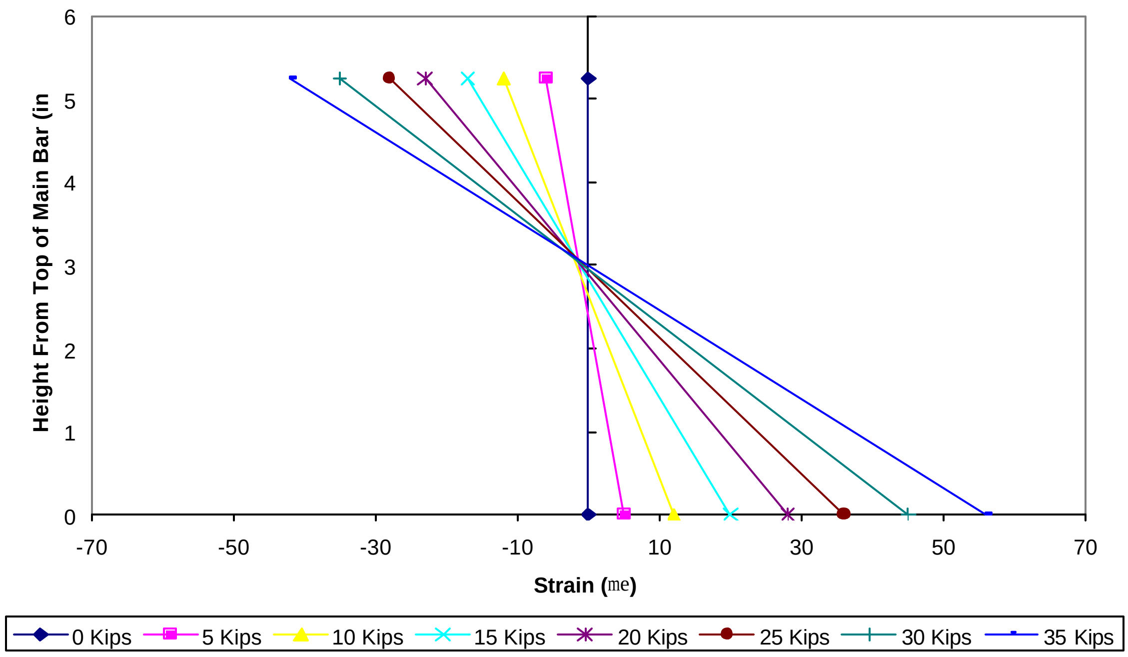

Figure B-118 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-450K Cycles

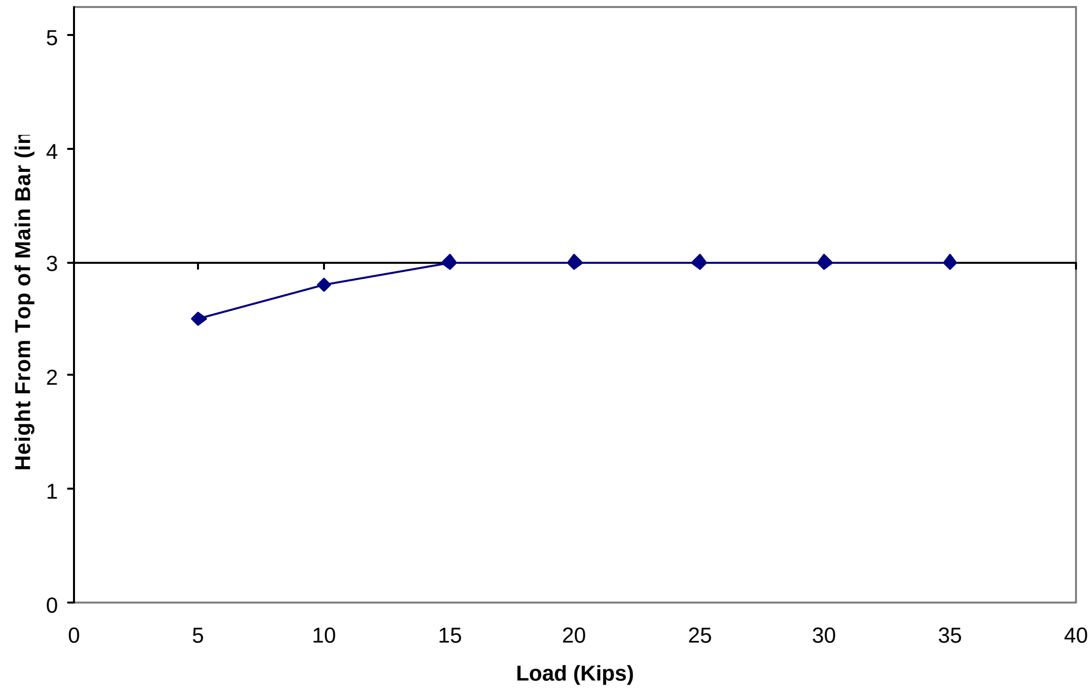

Figure B-119 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-450K Cycles

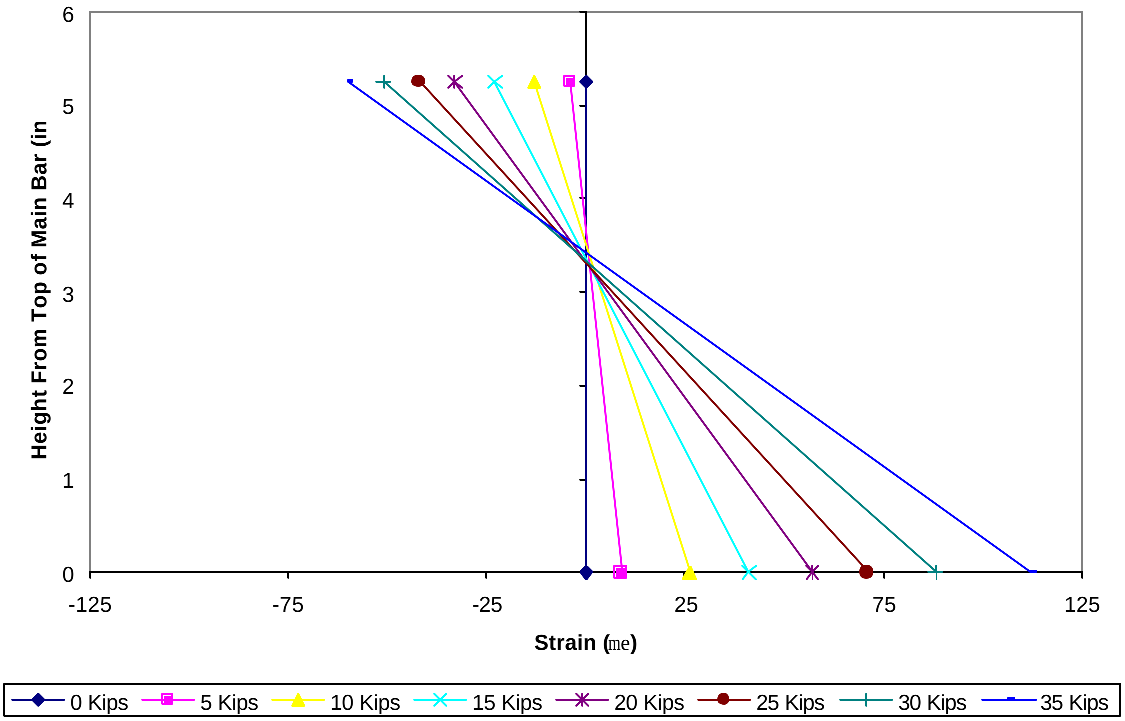

Figure B-120 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-450K Cycles

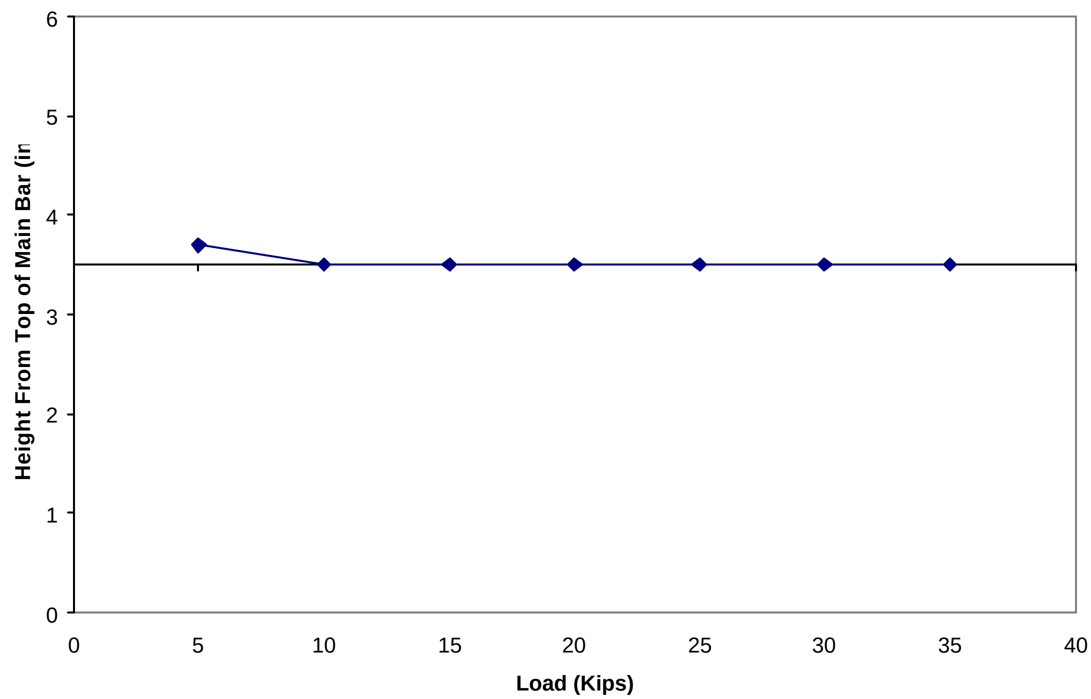

Figure B-121 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-450K Cycles

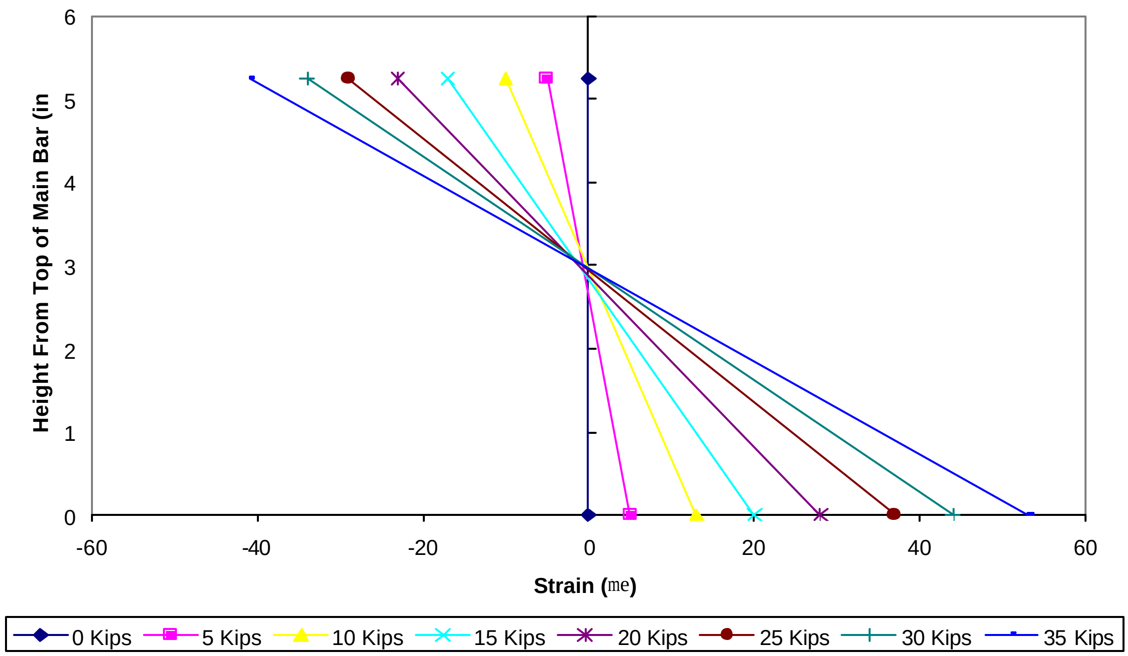

Figure B-122 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-600K Cycles

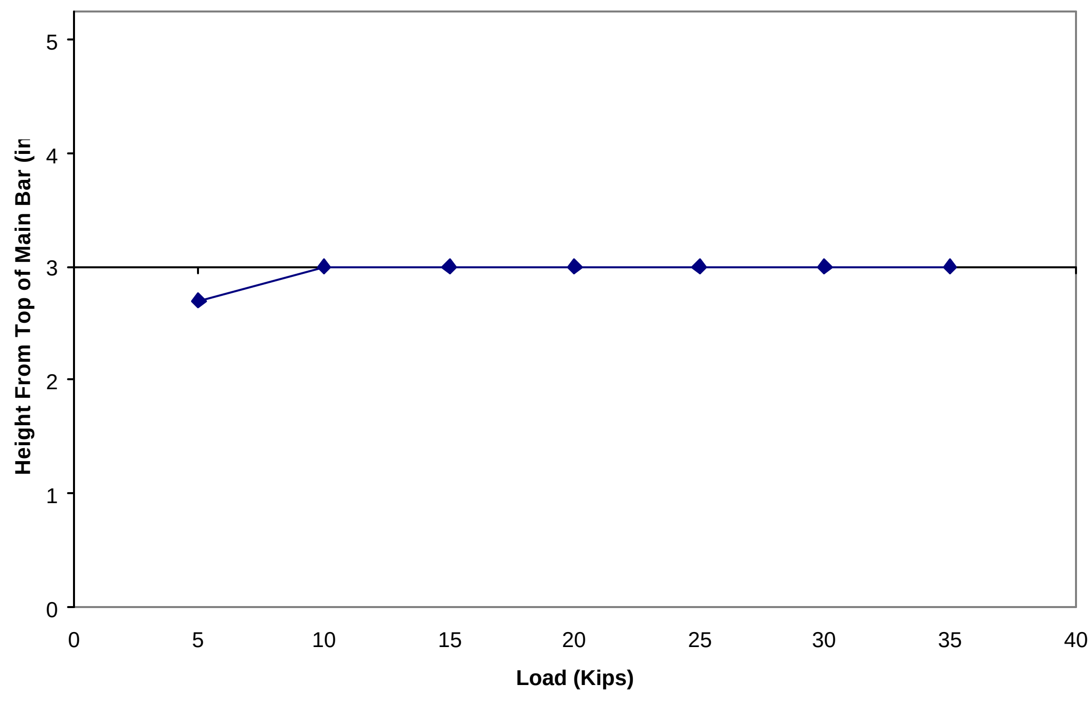

Figure B-123 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-600K Cycles

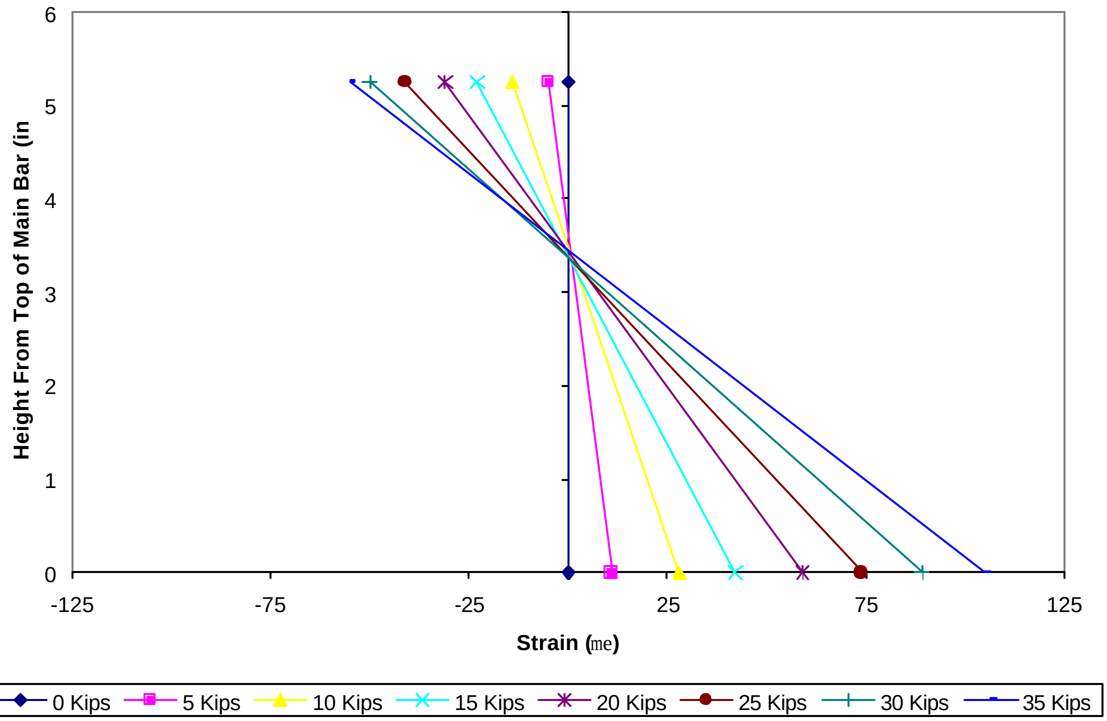

Figure B-124 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-600K Cycles

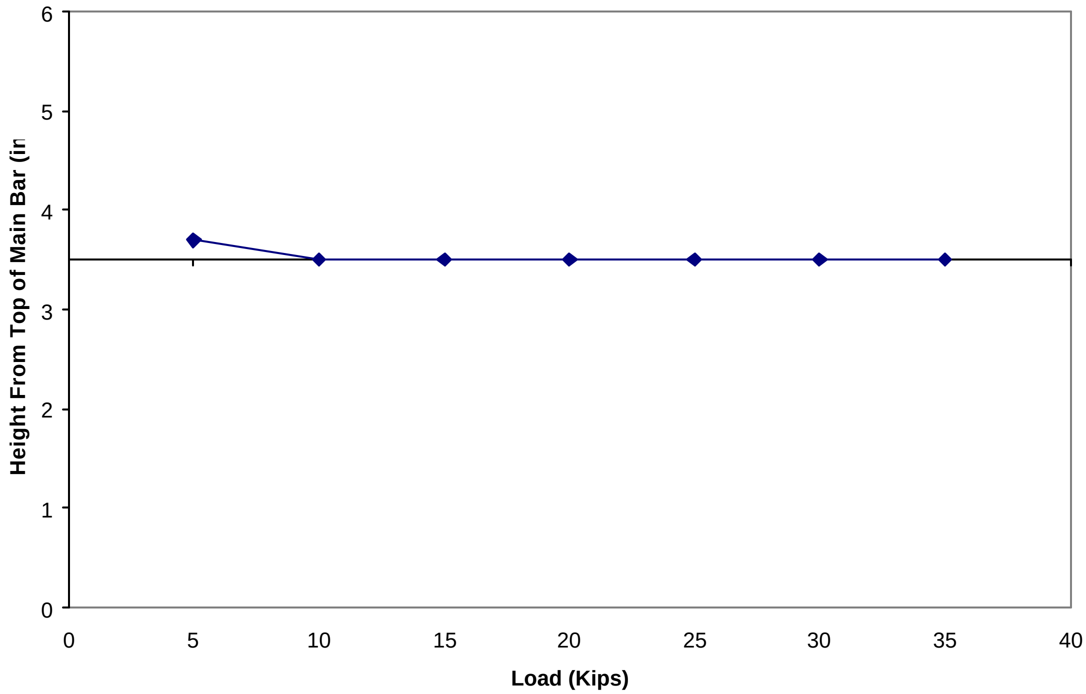

Figure B-125 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-600K Cycles

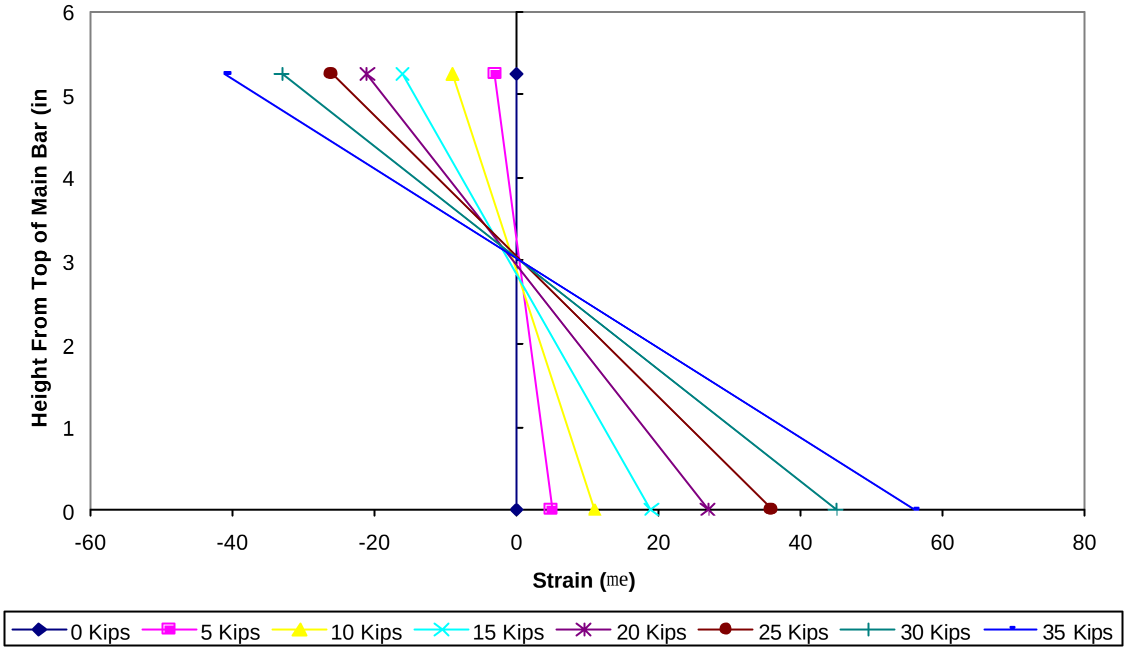

Figure B-126 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-750K Cycles

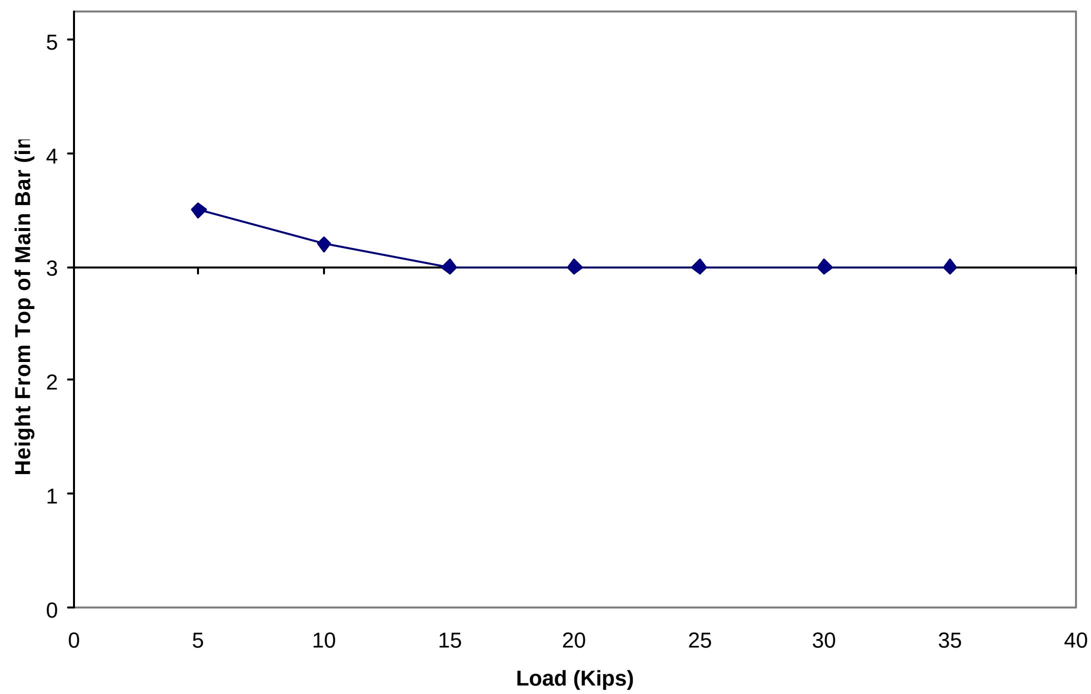

Figure B-127 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-750K Cycles

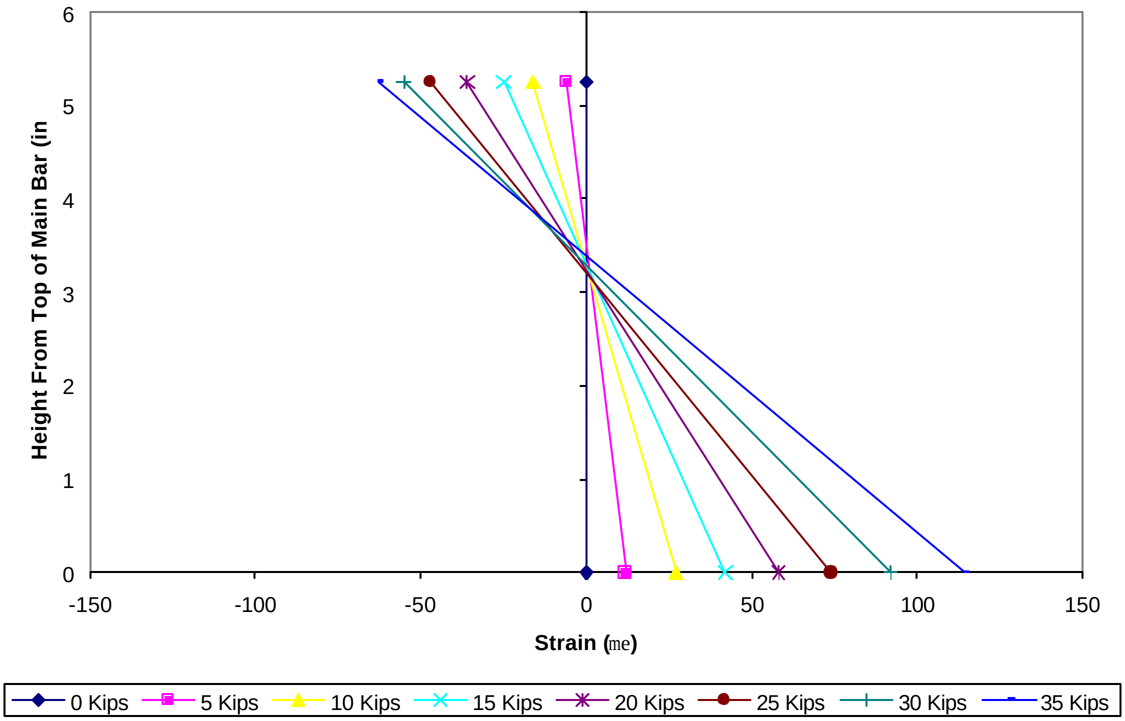

Figure B-128 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-750K Cycles

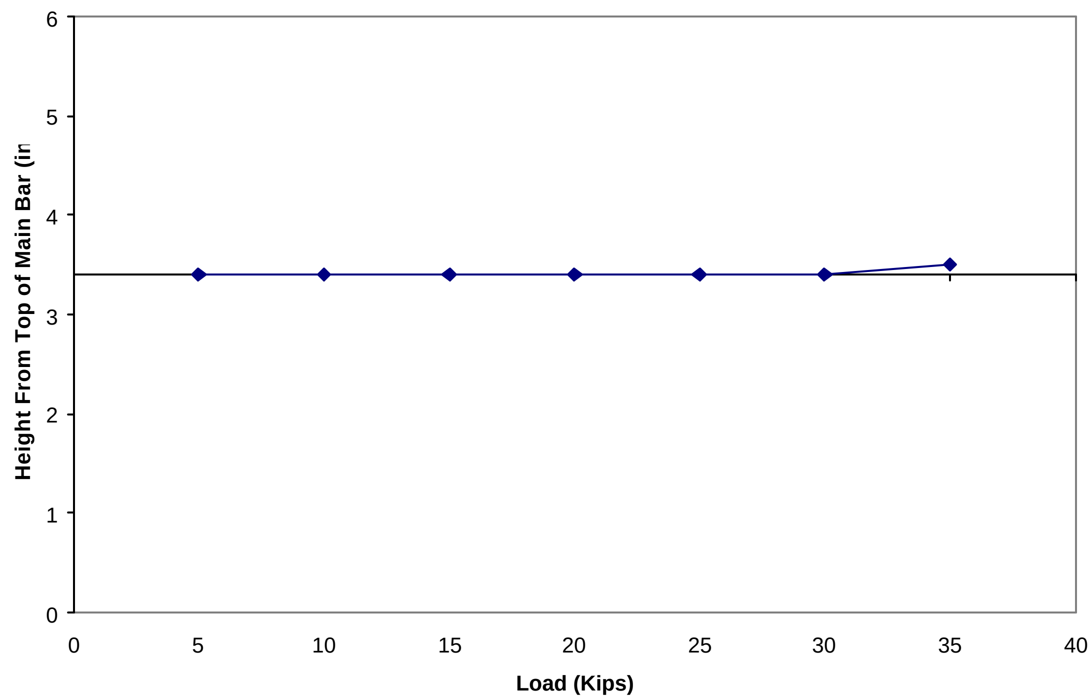

Figure B-129 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-750K Cycles

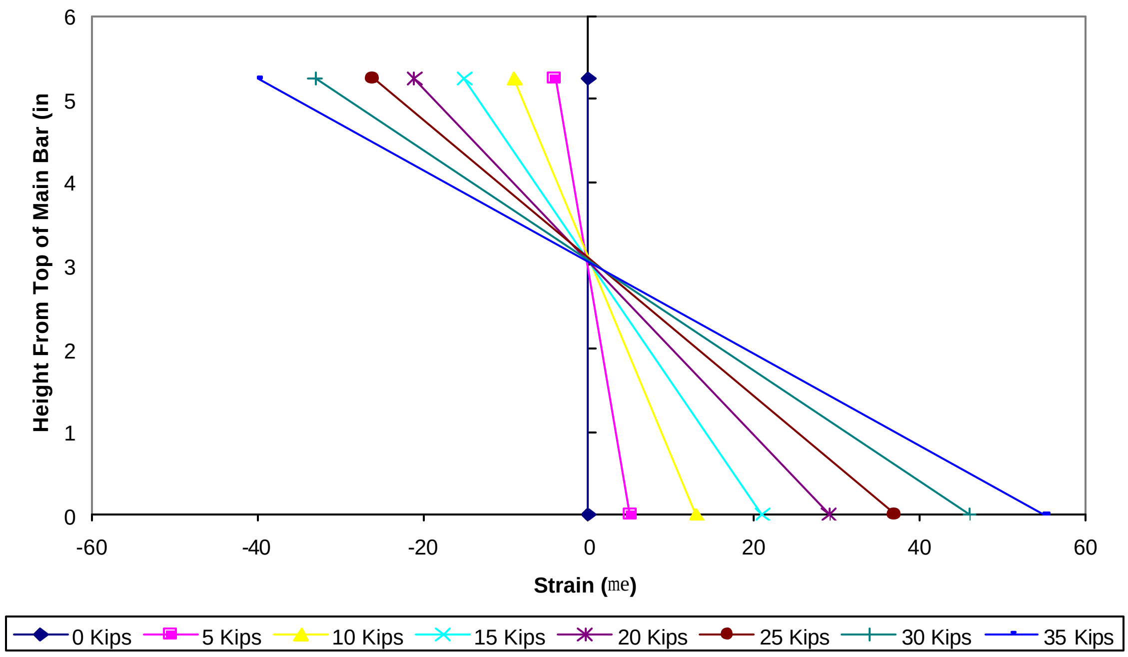

Figure B-130 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-900K Cycles

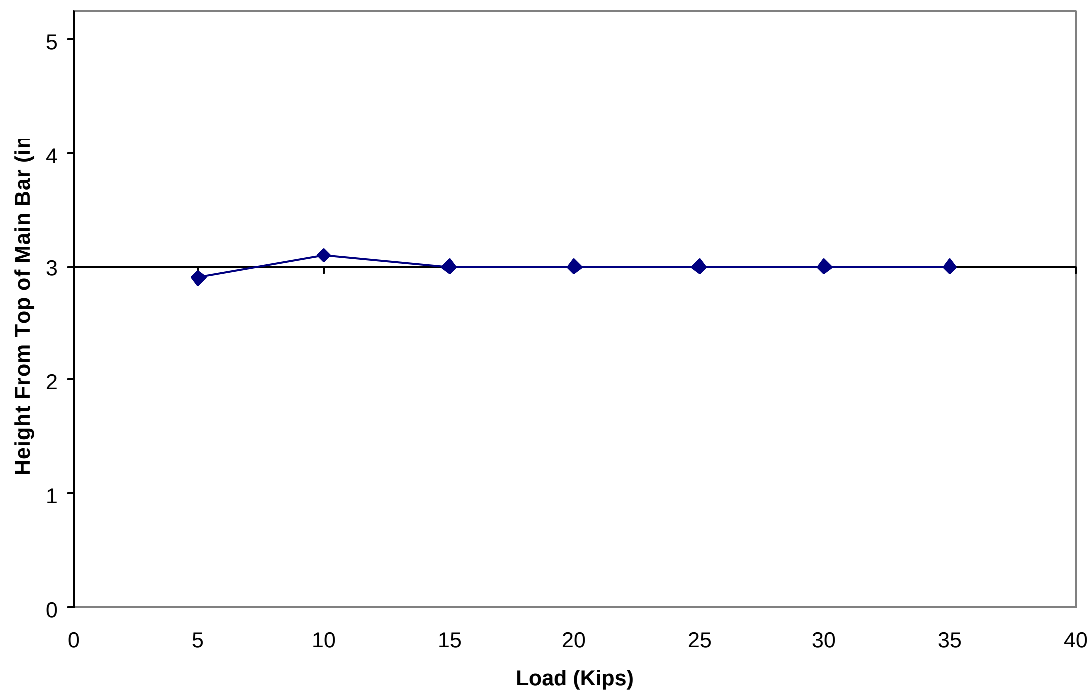

Figure B-131 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-900K Cycles

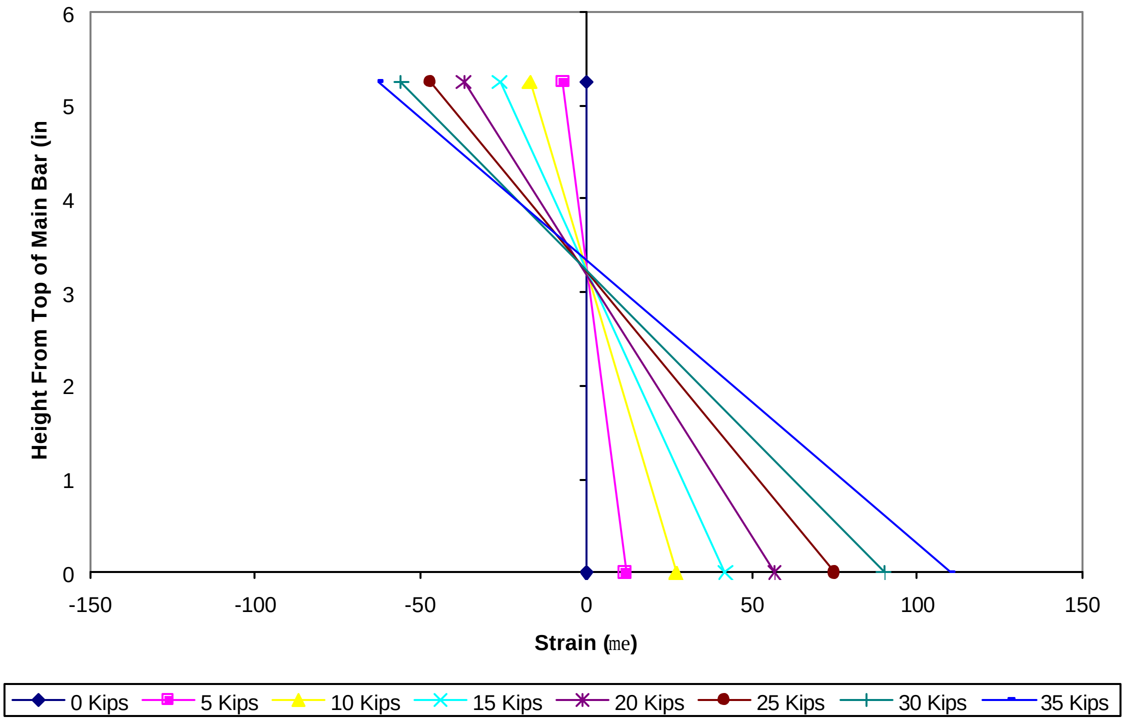

Figure B-132 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-900K Cycles

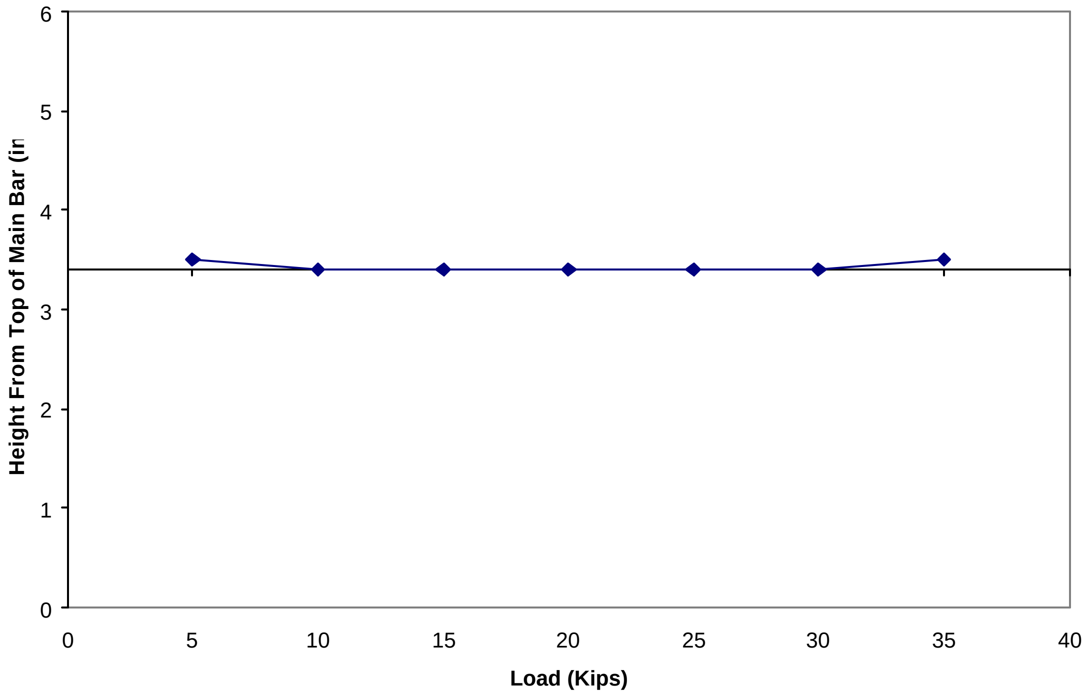

Figure B-133 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-900K Cycles

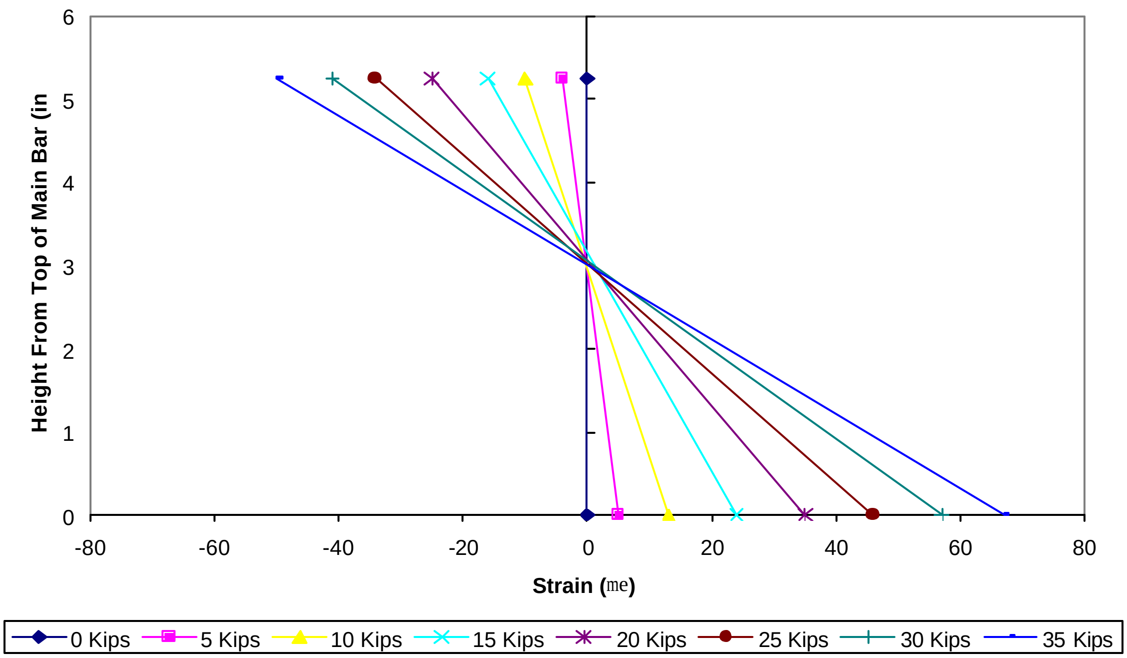

Figure B-134 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-1050K Cycles

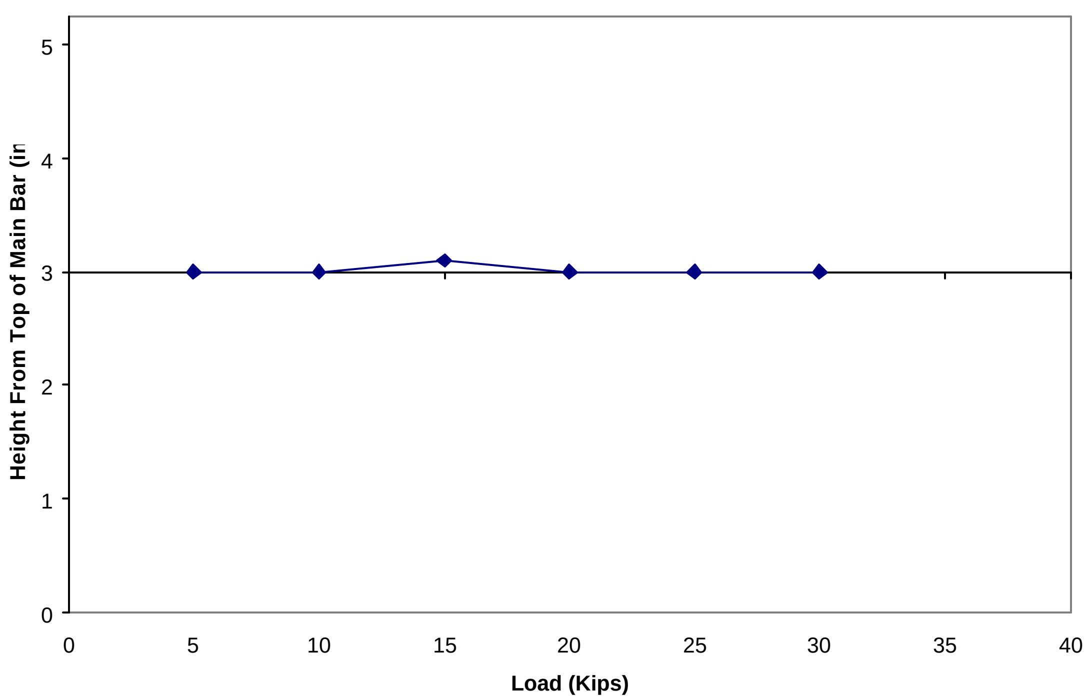

Figure B-135 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-1050K Cycles

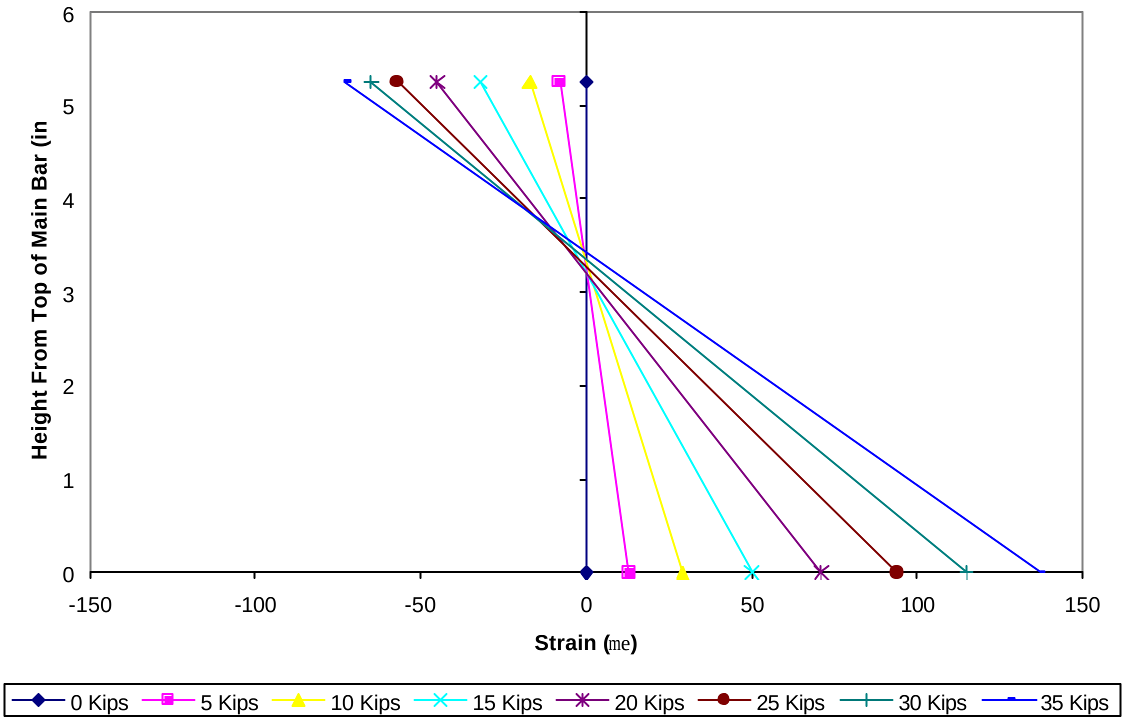

Figure B-136 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-1050K Cycles

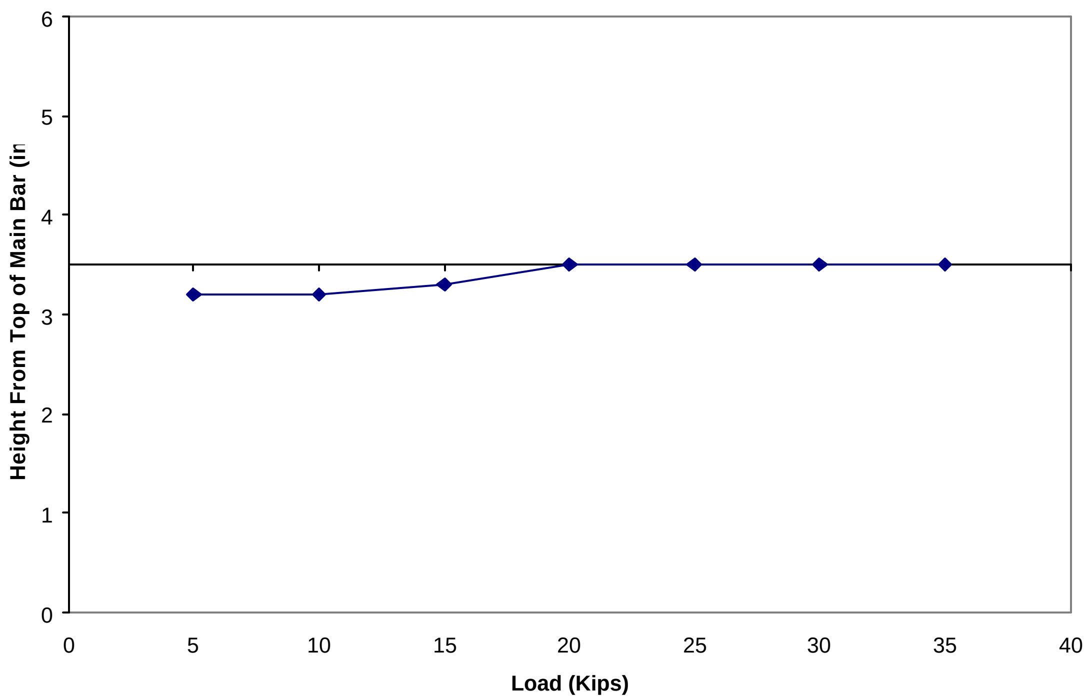

Figure B-137 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-1050K Cycles

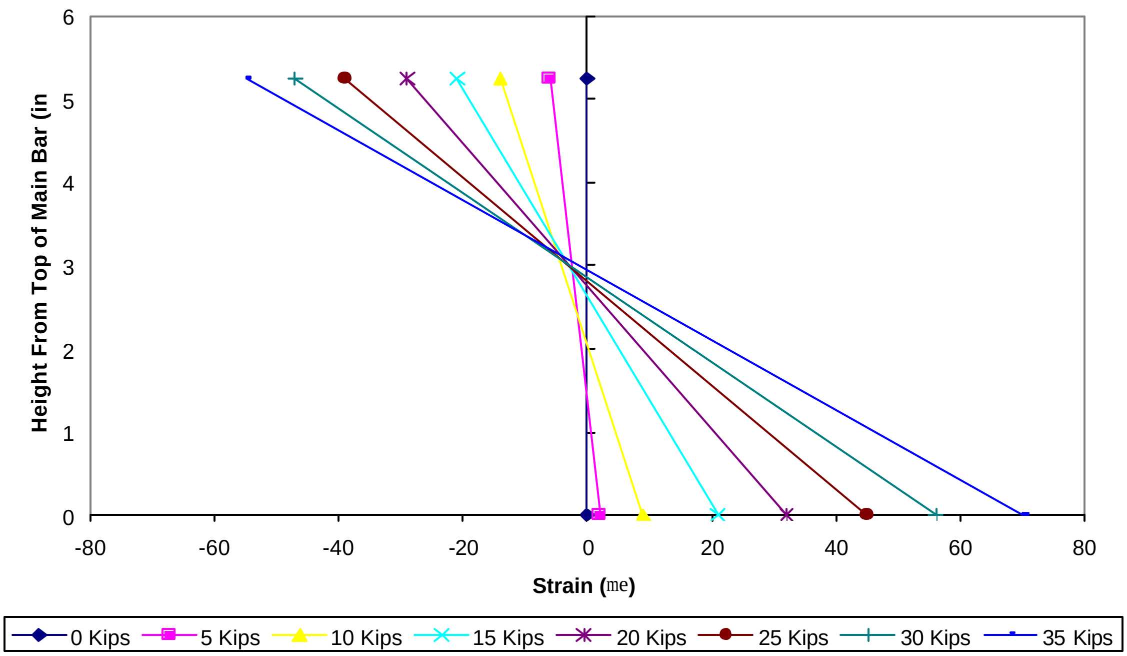

Figure B-138 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-1200K Cycles

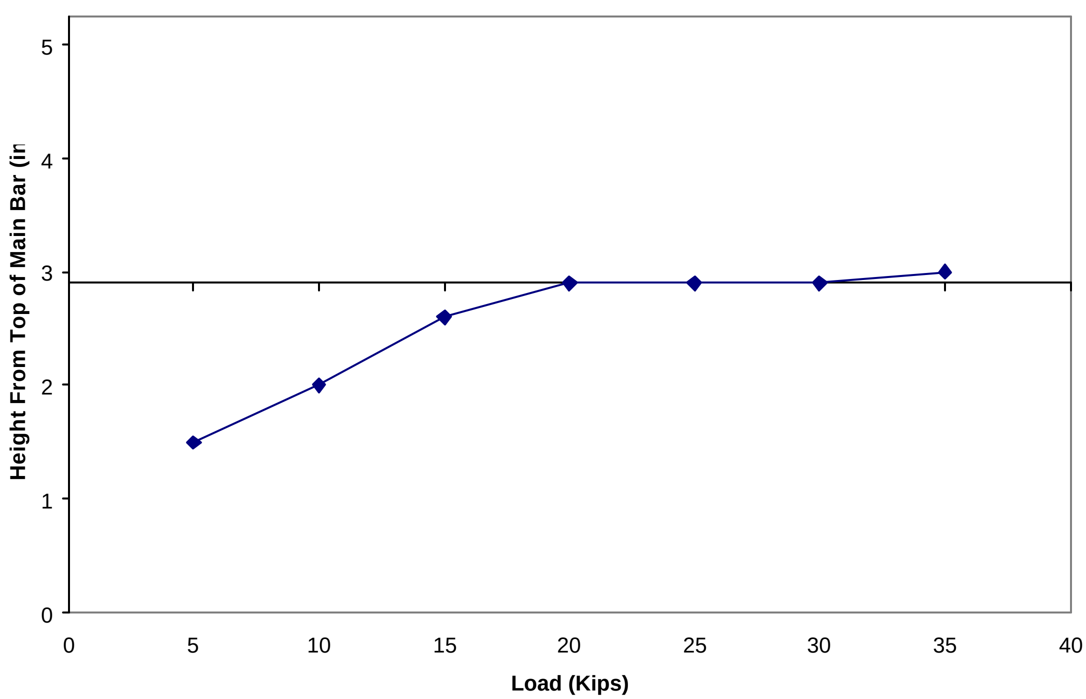

Figure B-139 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-1200K Cycles

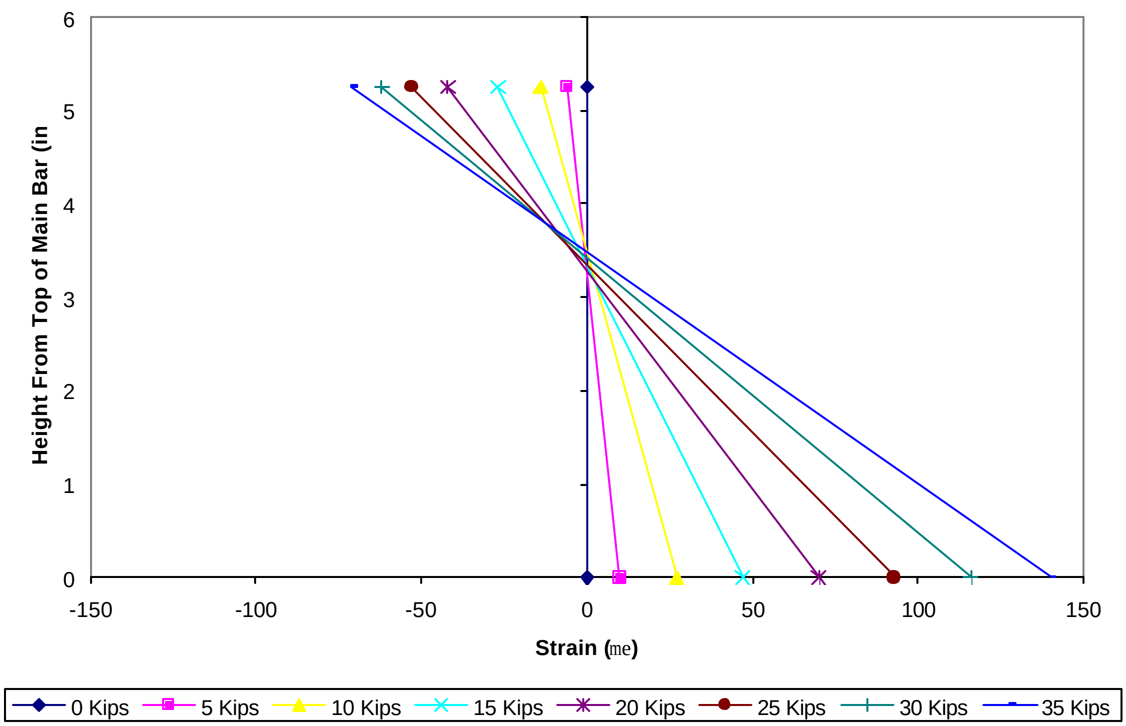

Figure B-140 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-1200K Cycles

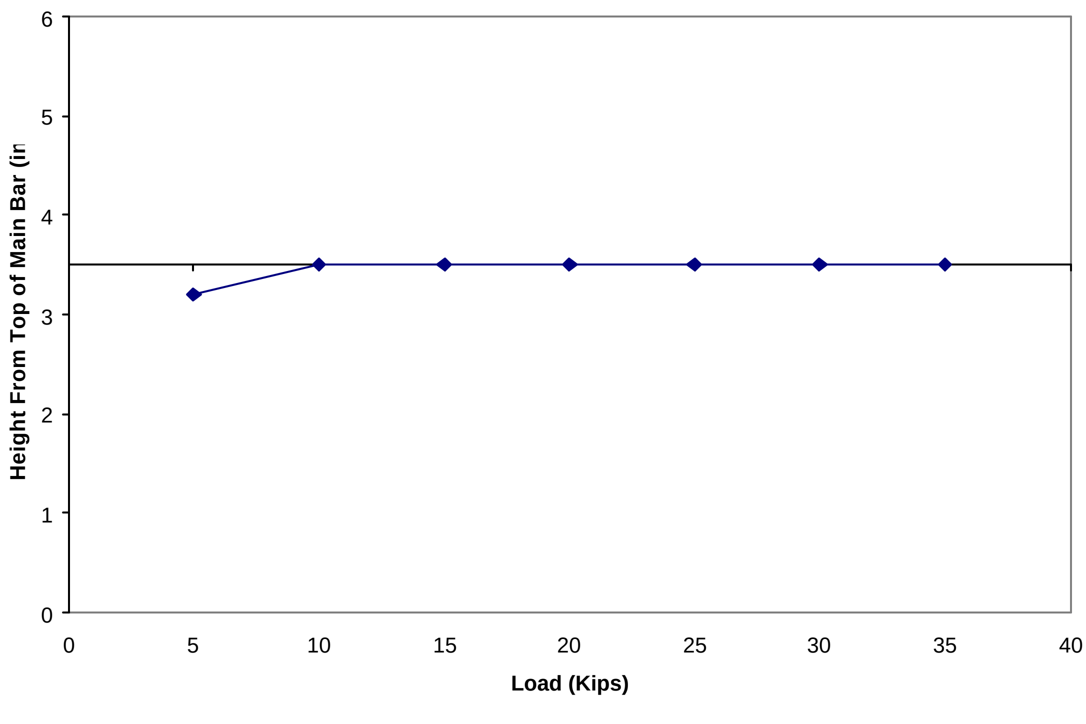

Figure B-141 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-1200K Cycles

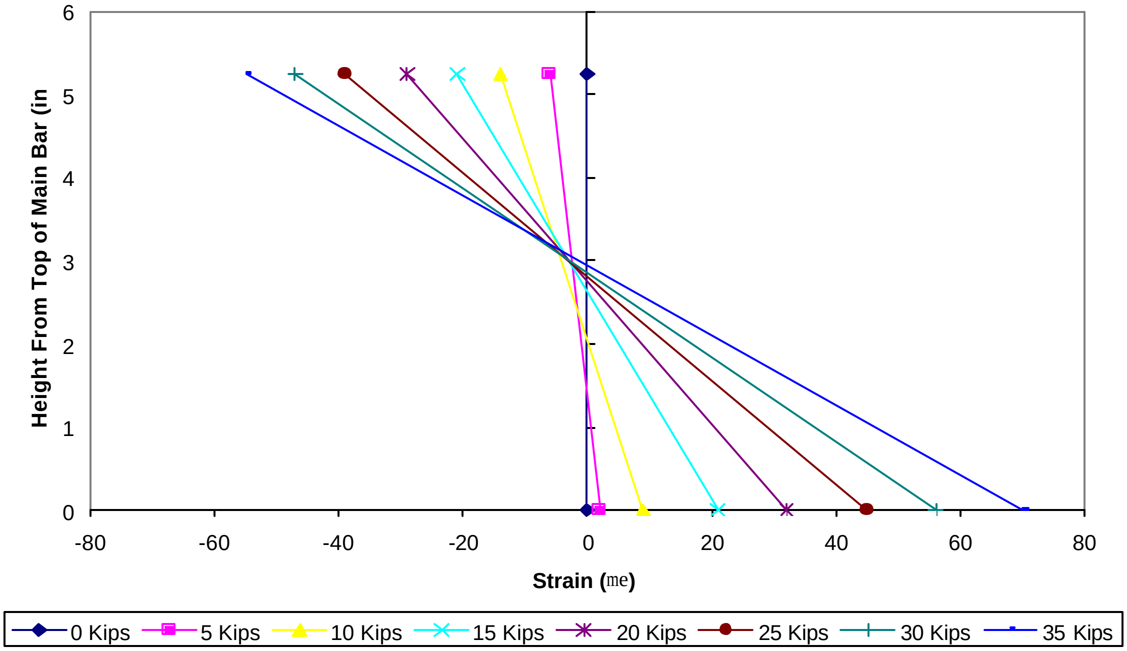

Figure B-142 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-1350K Cycles

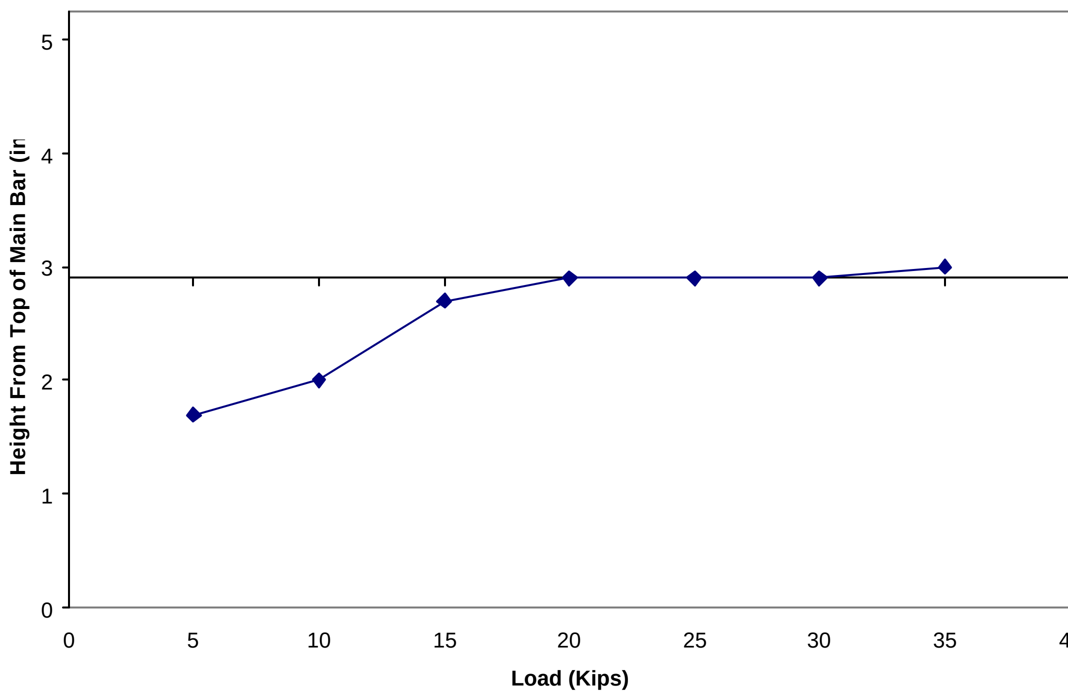

Figure B-143 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-1350K Cycles

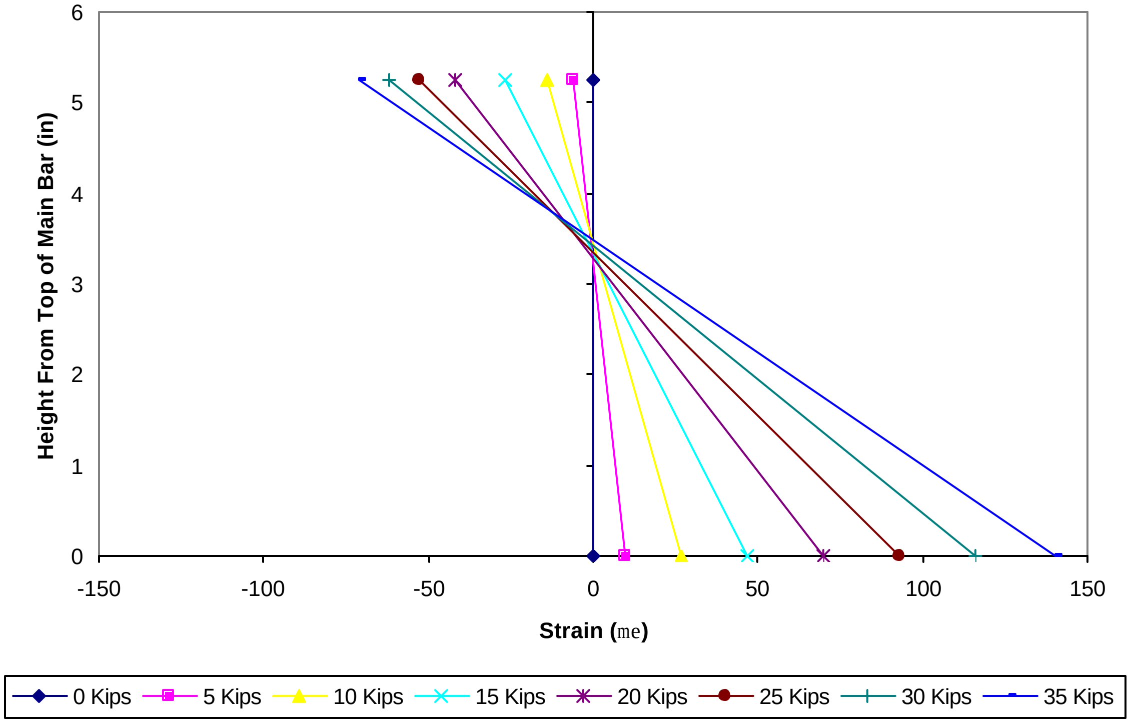

Figure B-144 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-1350K Cycles

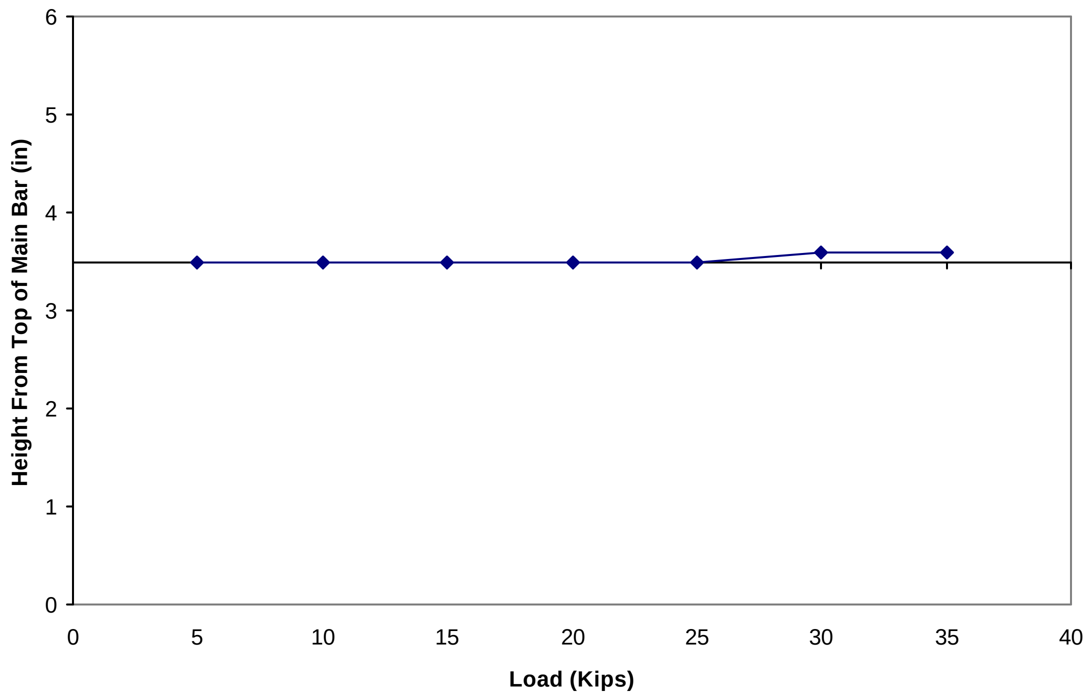

Figure B-145 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-1350K Cycles

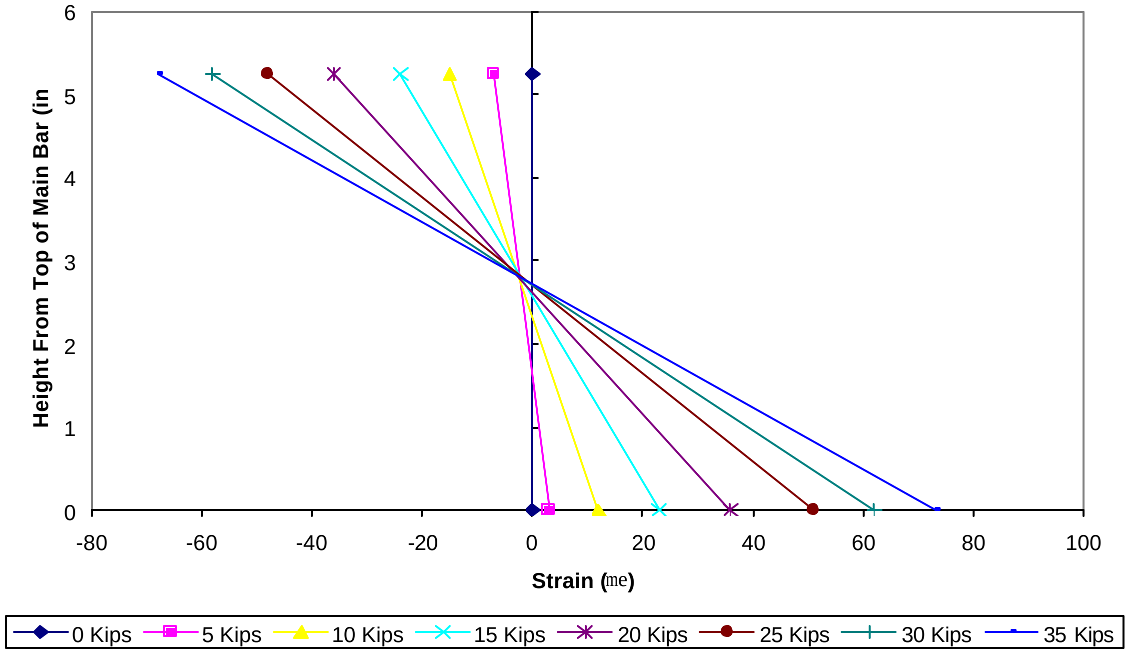

Figure B-146 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-1500K Cycles

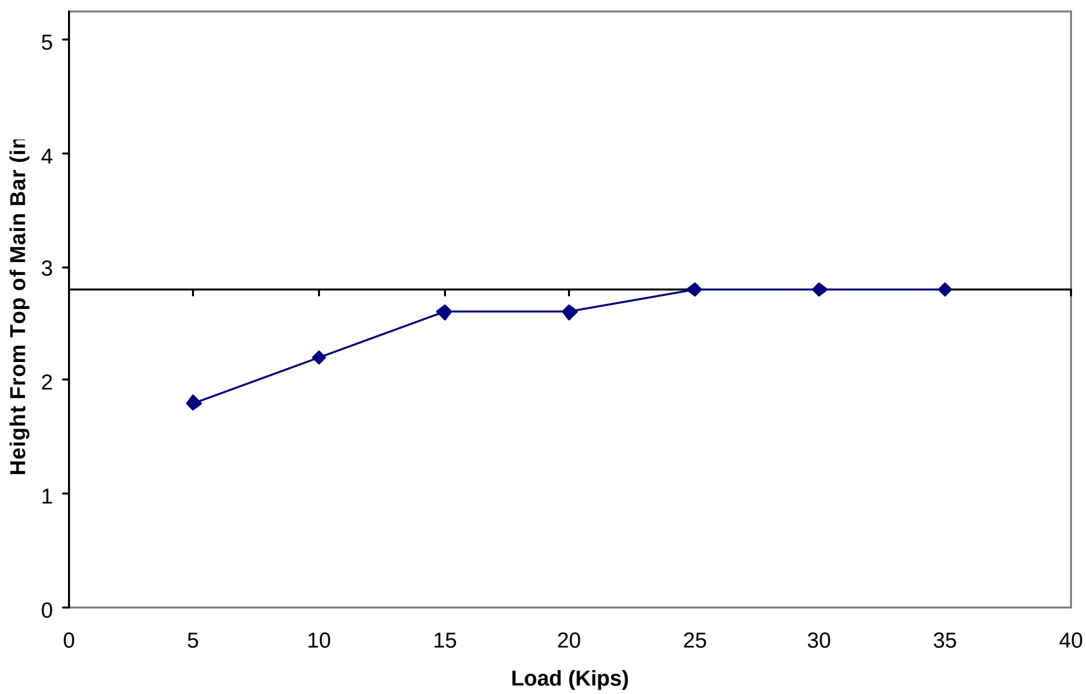

Figure B-147 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-1500K Cycles

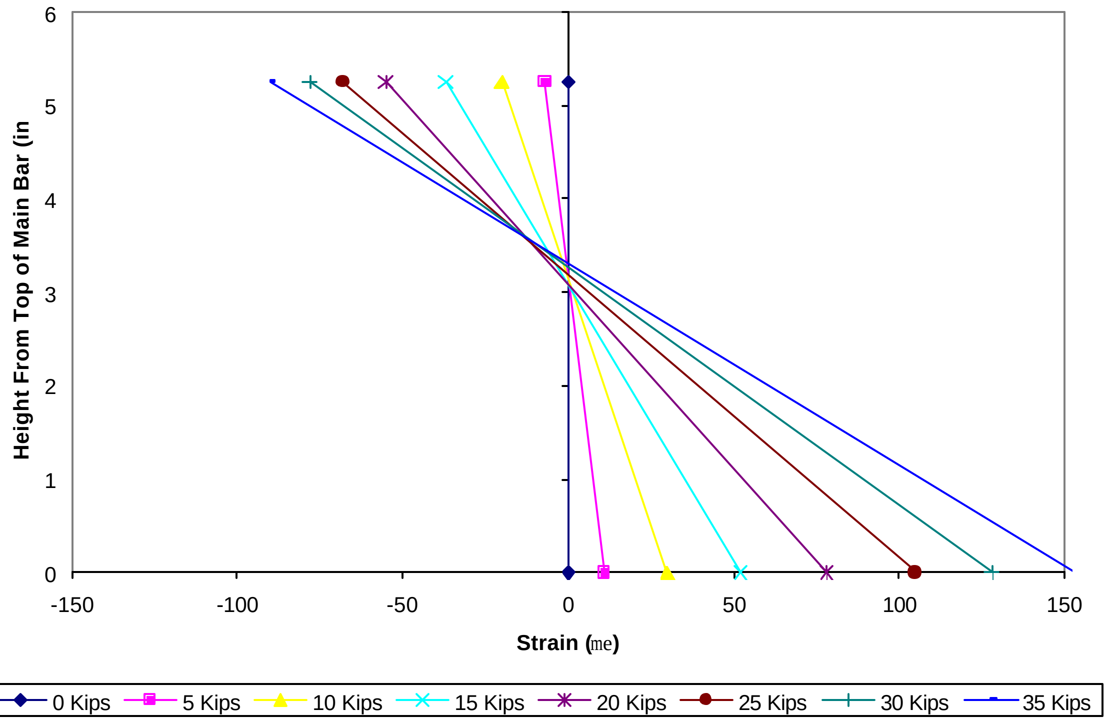

Figure B-148 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-1500K Cycles

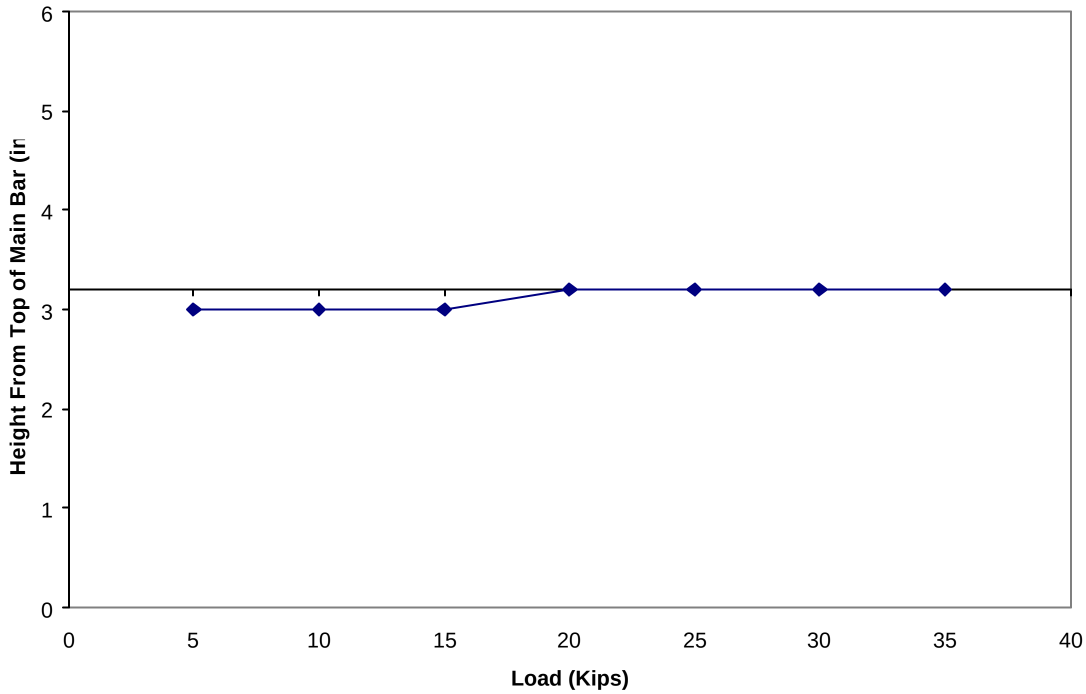

Figure B-149 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-1500K Cycles

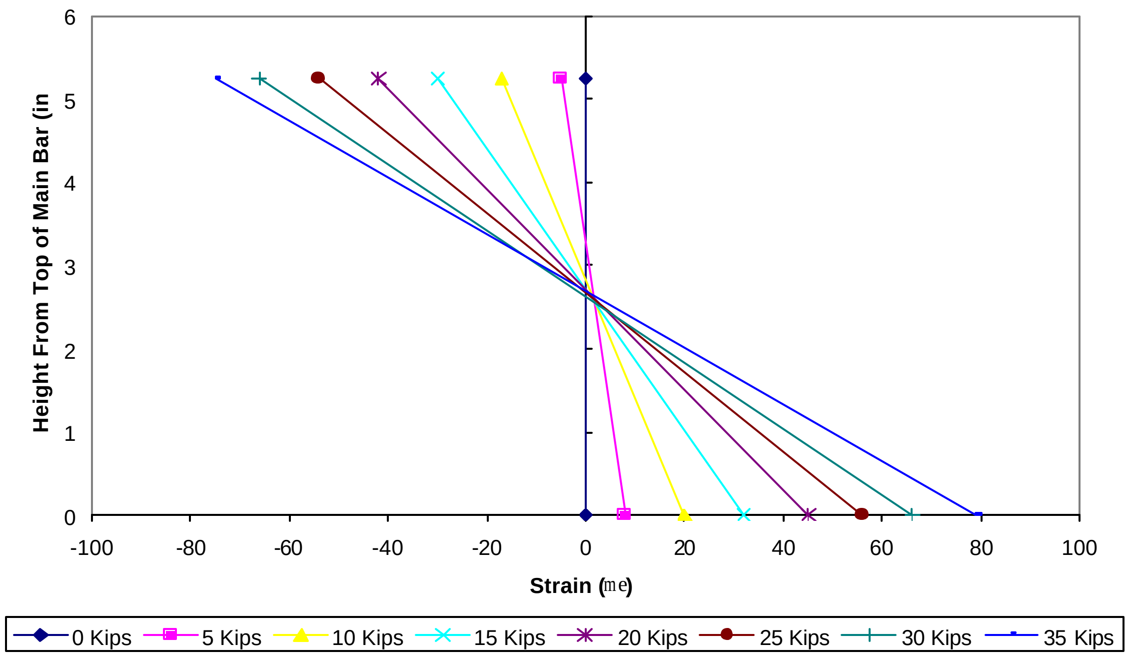

Figure B-150 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-1650K Cycles

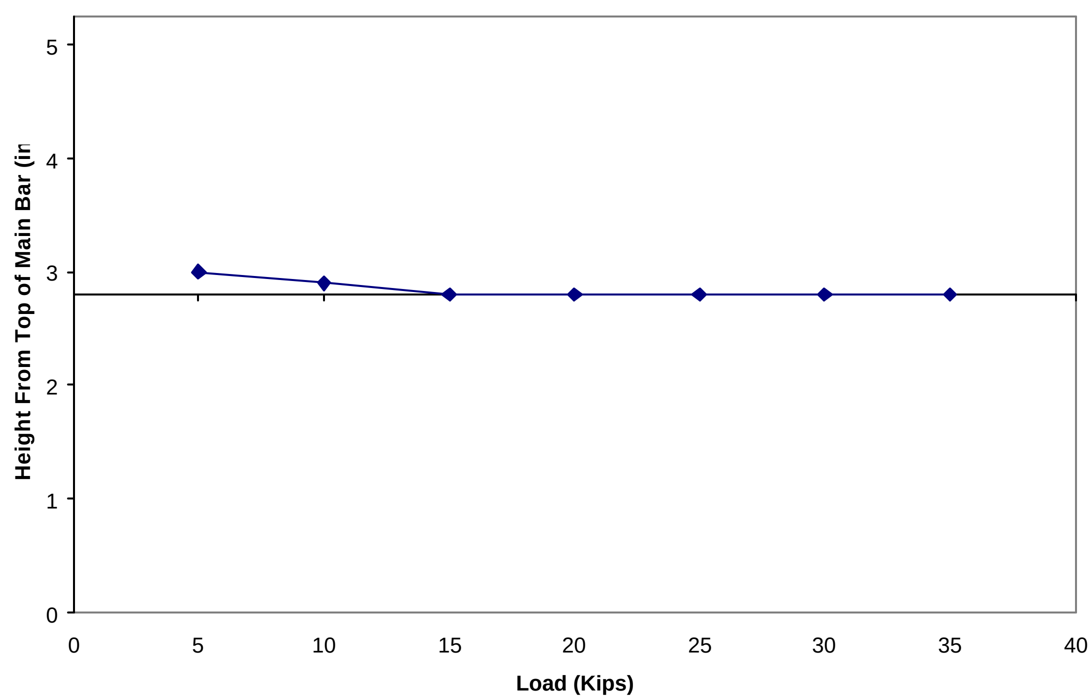

Figure B-151 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-1650K Cycles

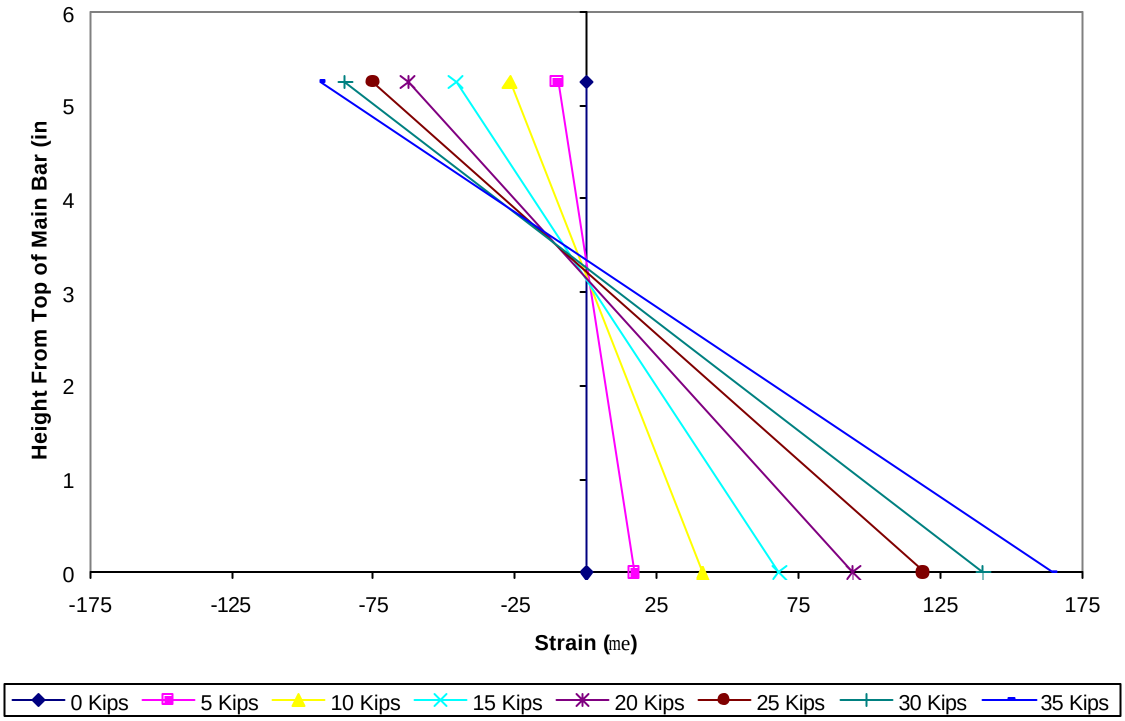

Figure B-152 Fatigue Specimen #1 Main Bar #2 -Cross-Sectional Strain Distribution-1650K Cycles

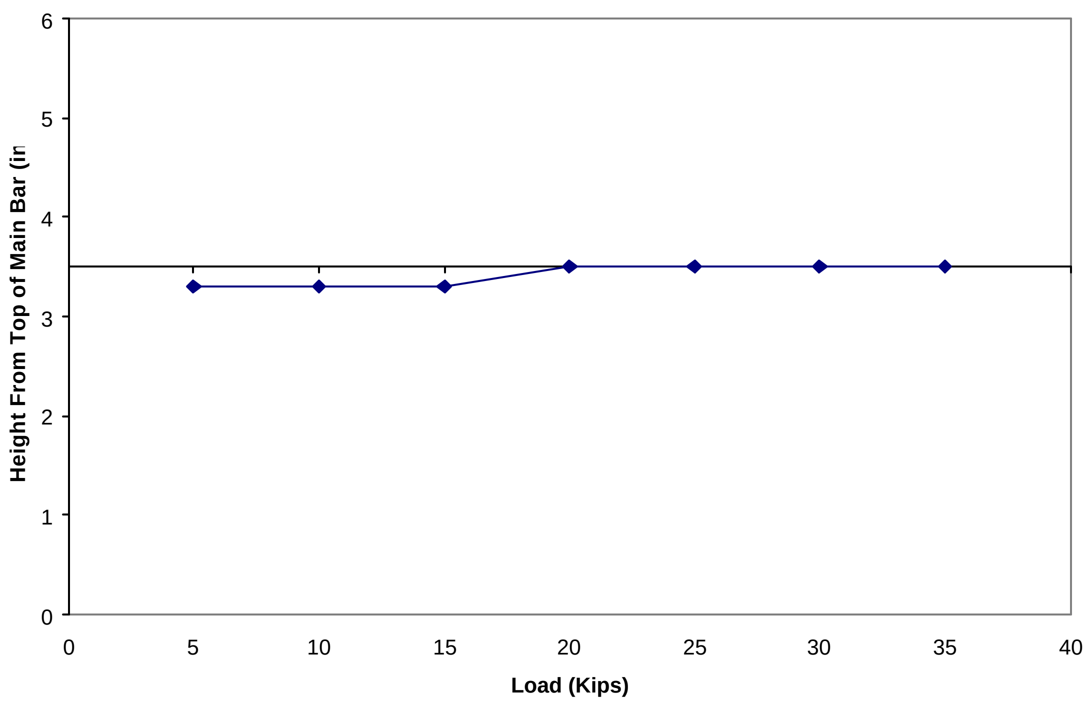

Figure B-153 Fatigue Specimen #1 Main Bar #2 -Neutral Axis Location-1650K Cycles

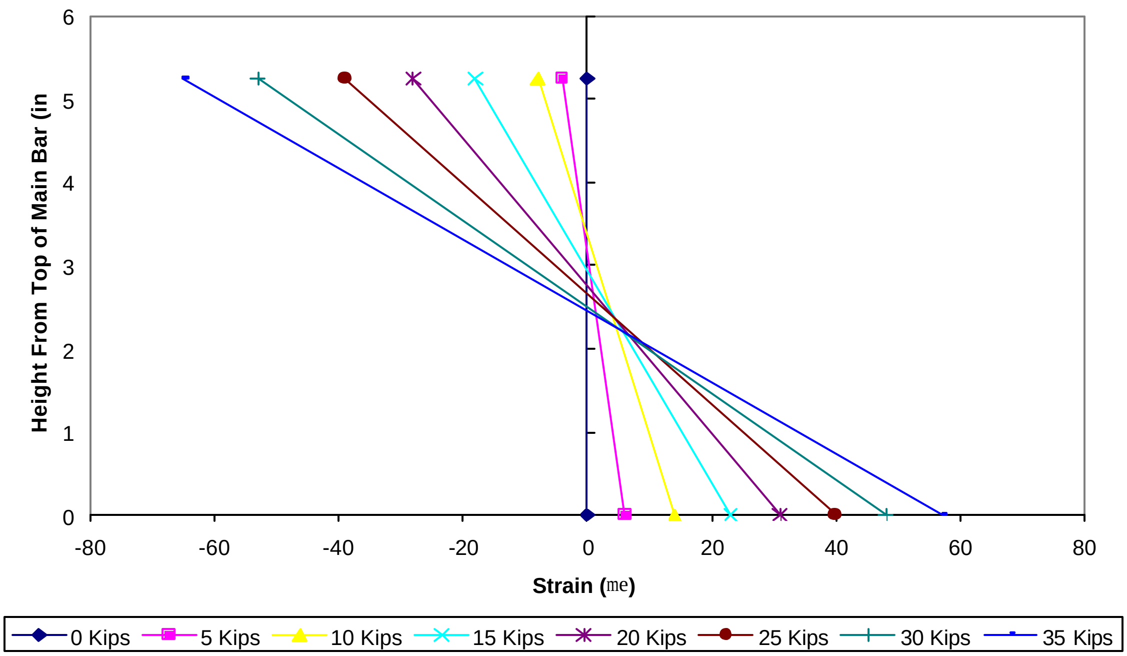

Figure B-154 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-1800K Cycles

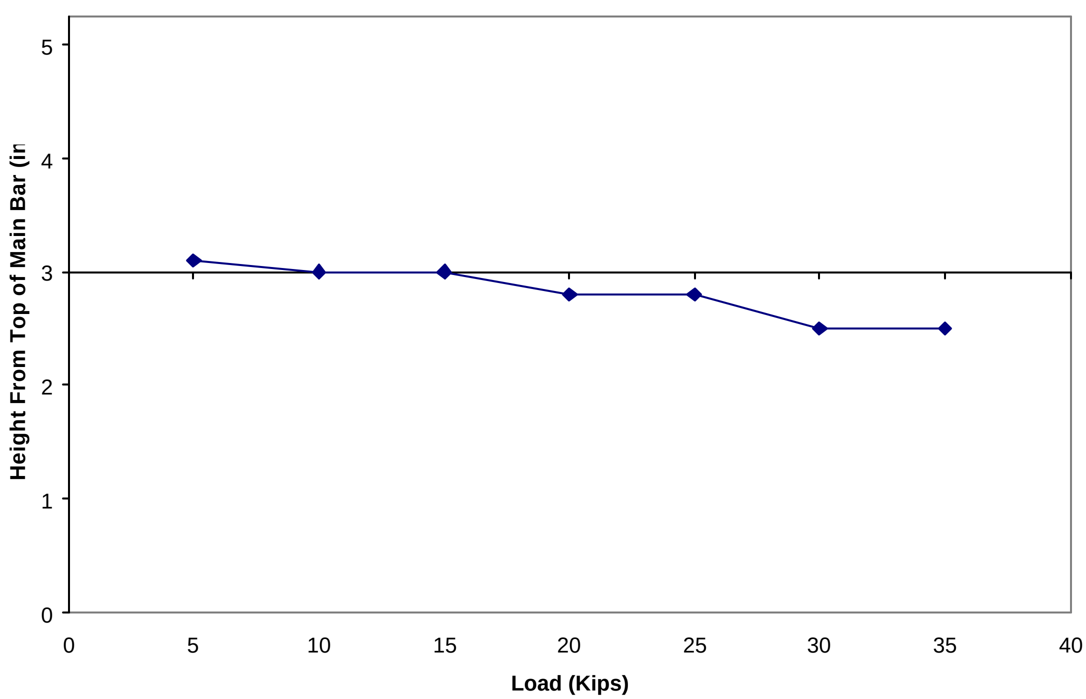

Figure B-155 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-1800K Cycles

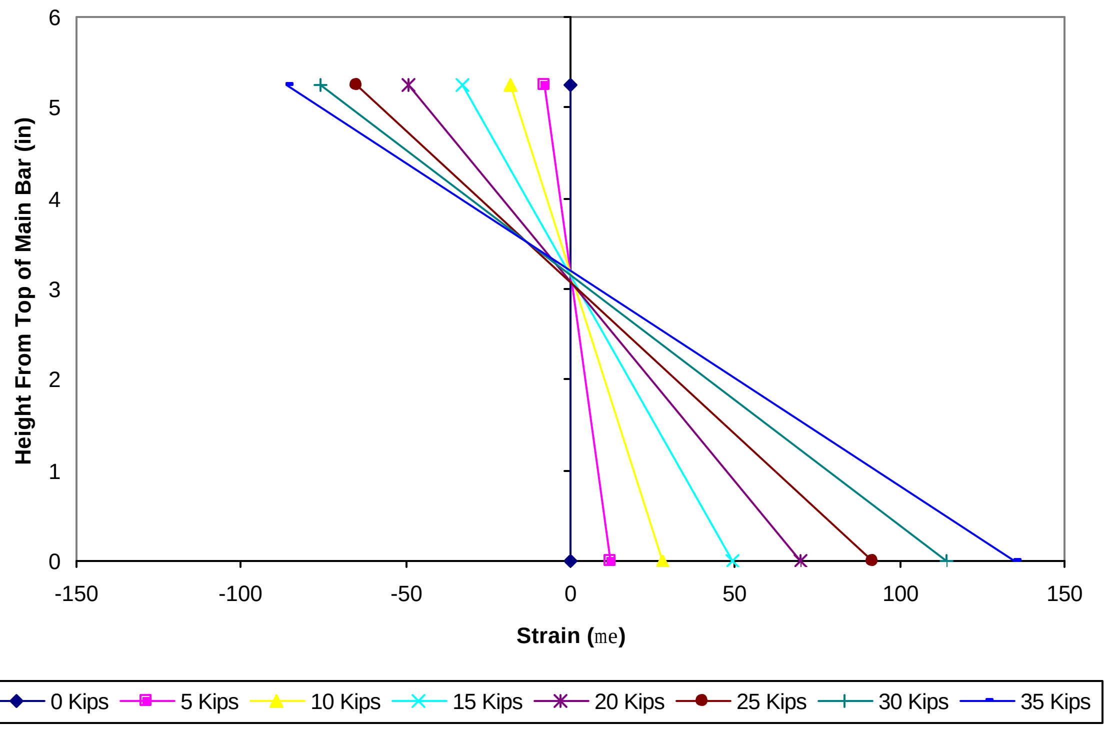

Figure B-156 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-1800K Cycles

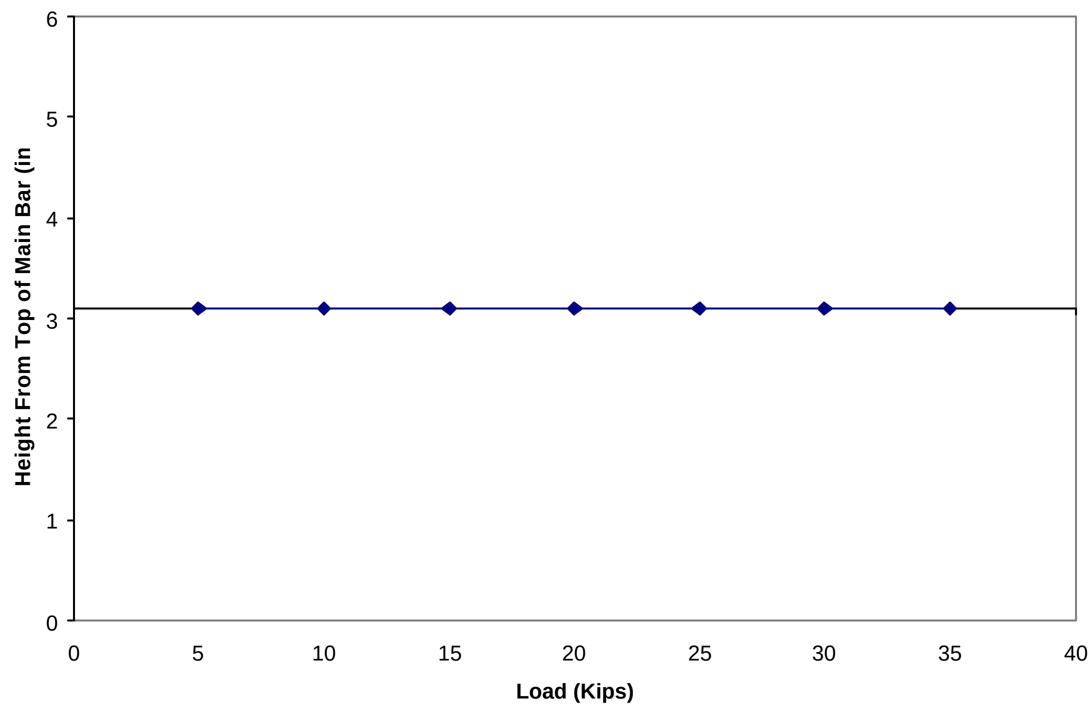

Figure B-157 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-1800K Cycles

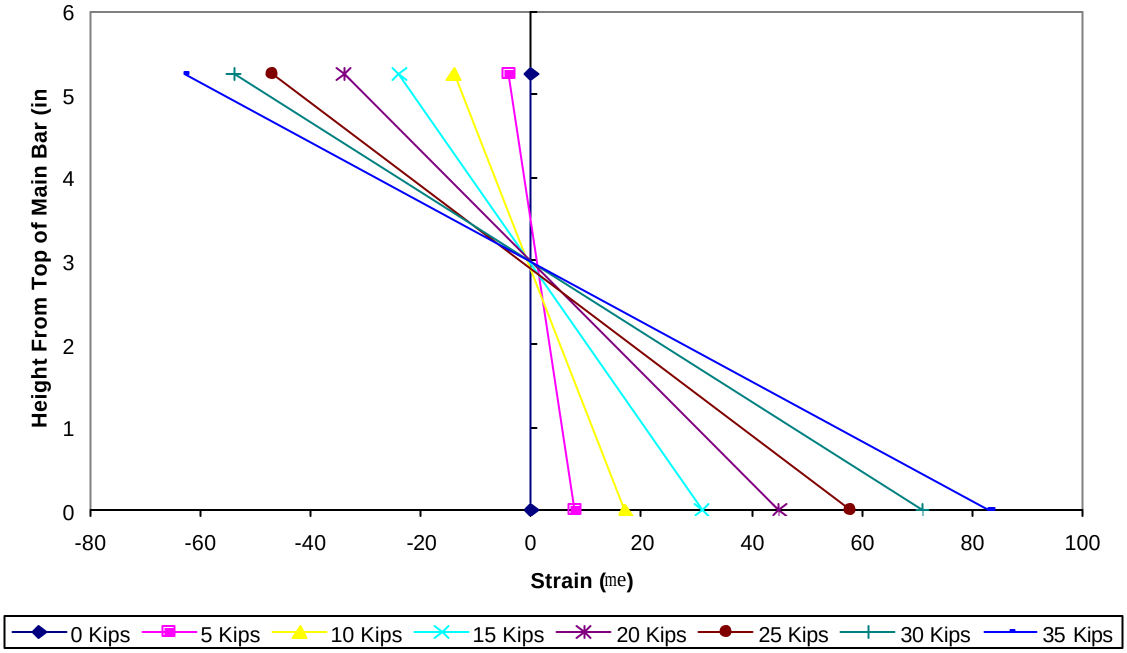

Figure B-158 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-1950K Cycles

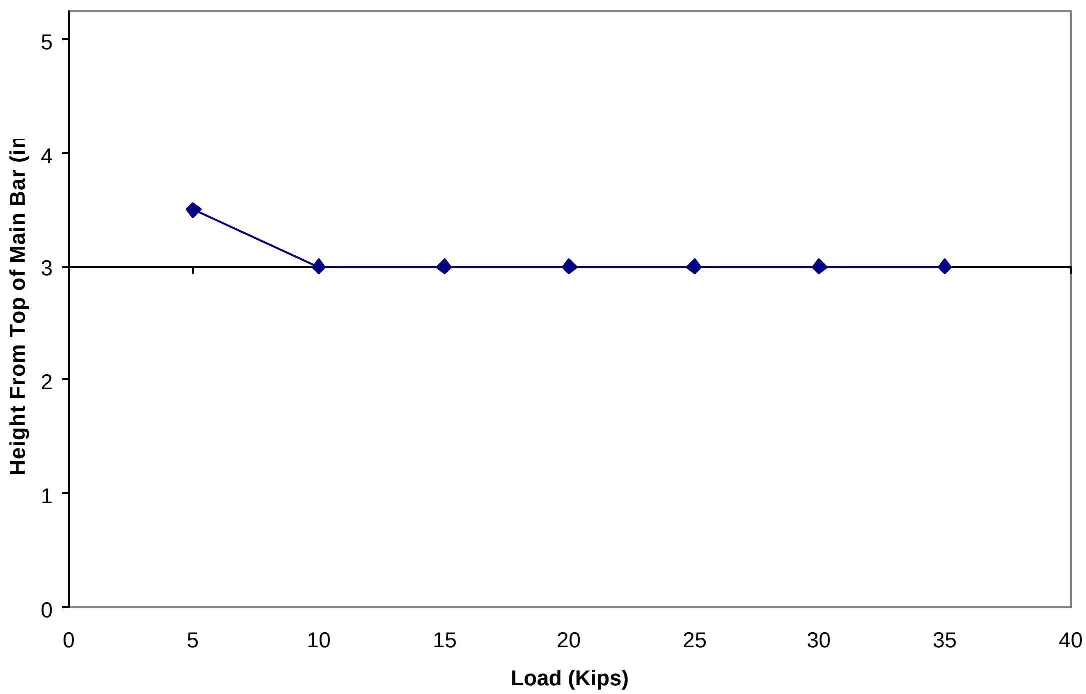

Figure B-159 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-1950K Cycles

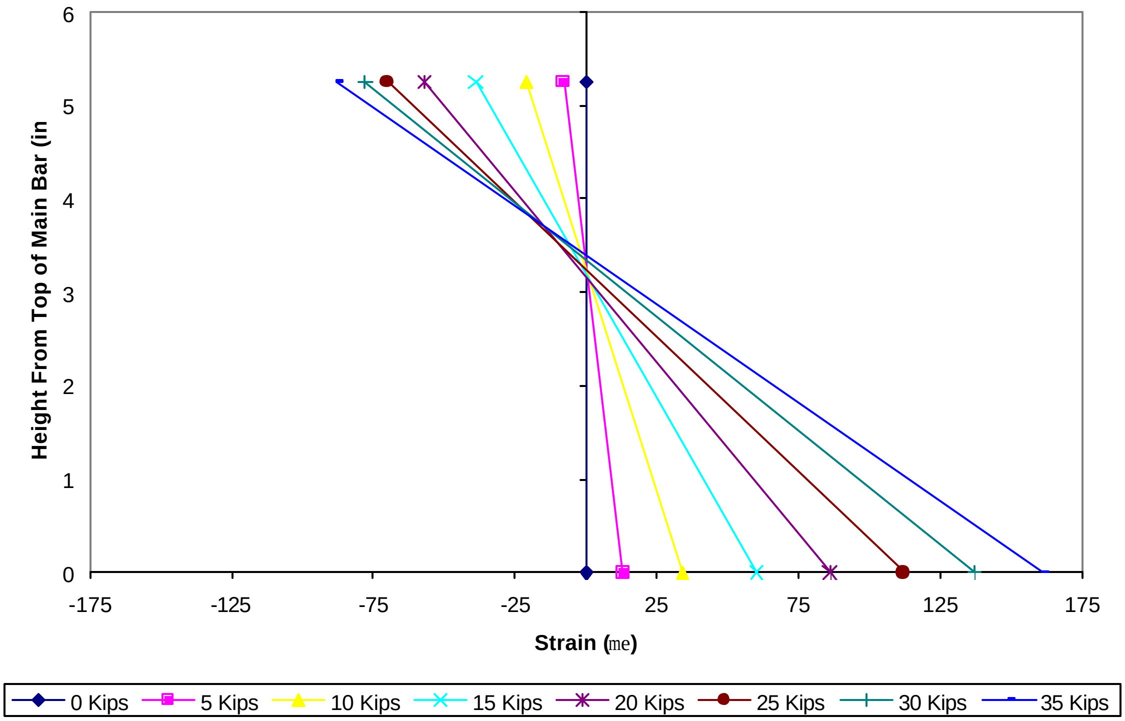

Figure B-160 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-1950K Cycles

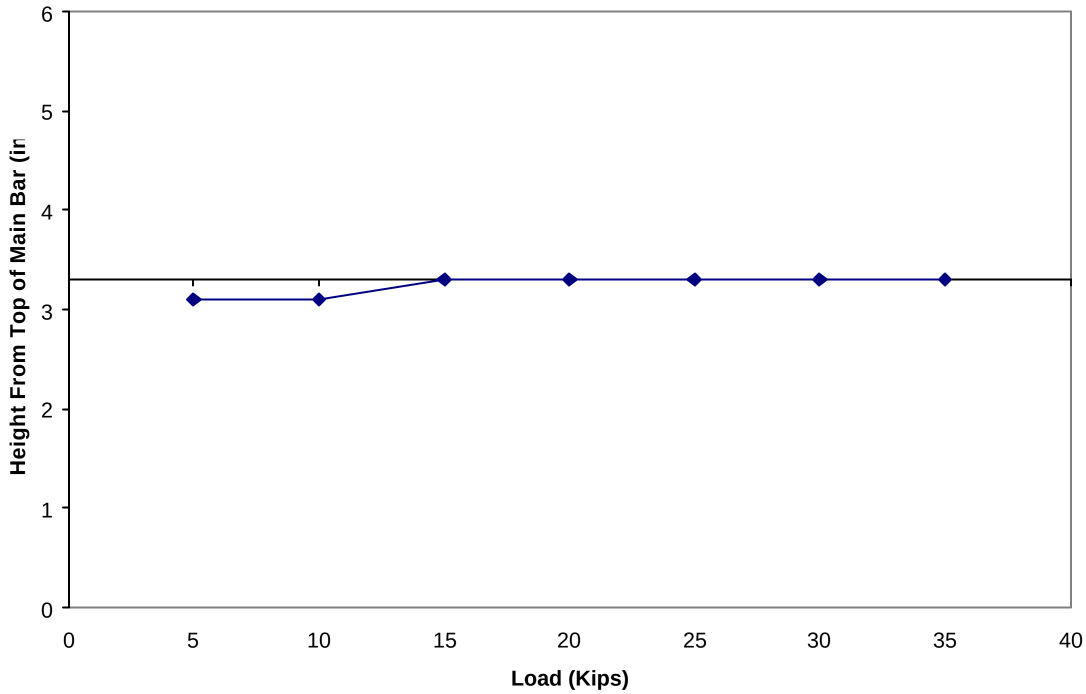

Figure B-161 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-1950K Cycles

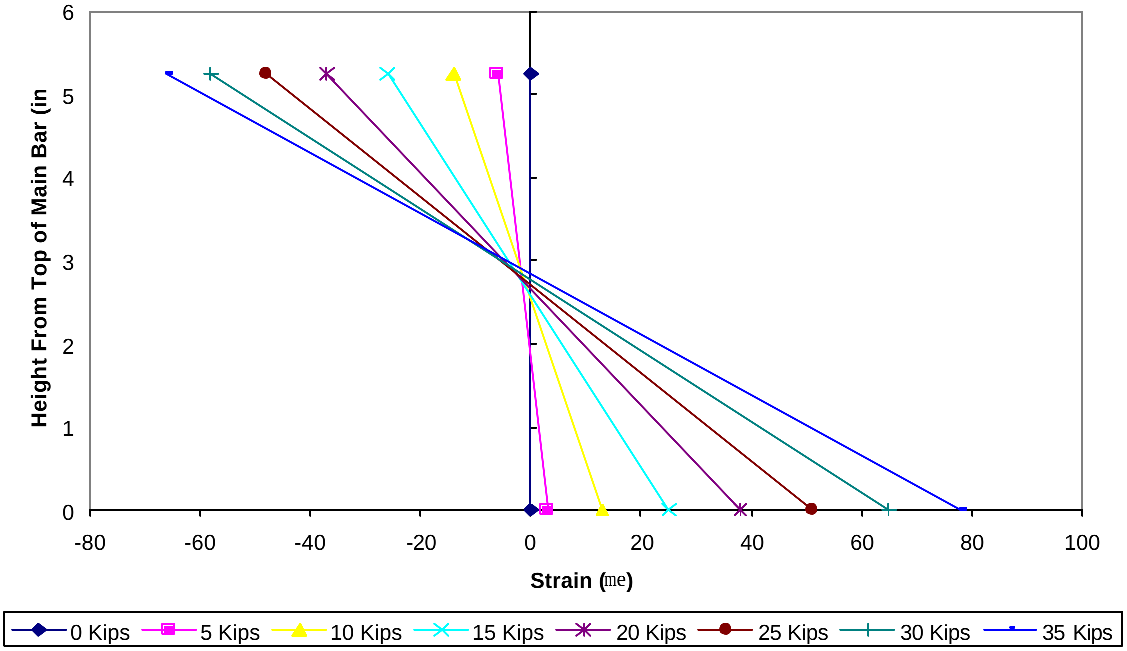

Figure B-162 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-2100K Cycles

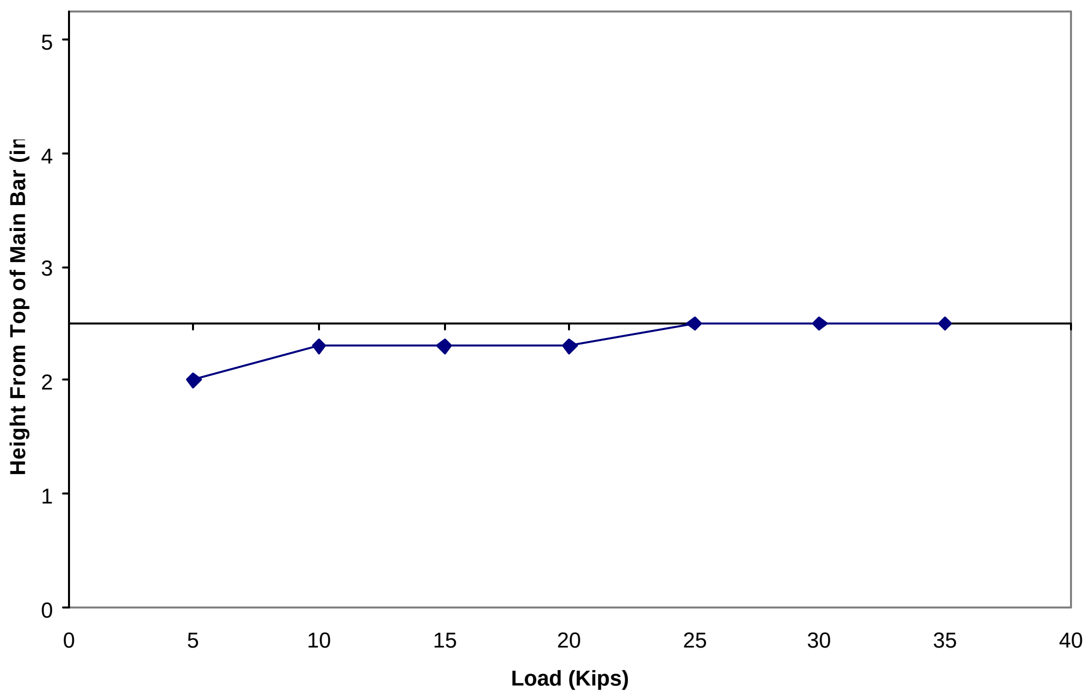

Figure B-163 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-2100K Cycles

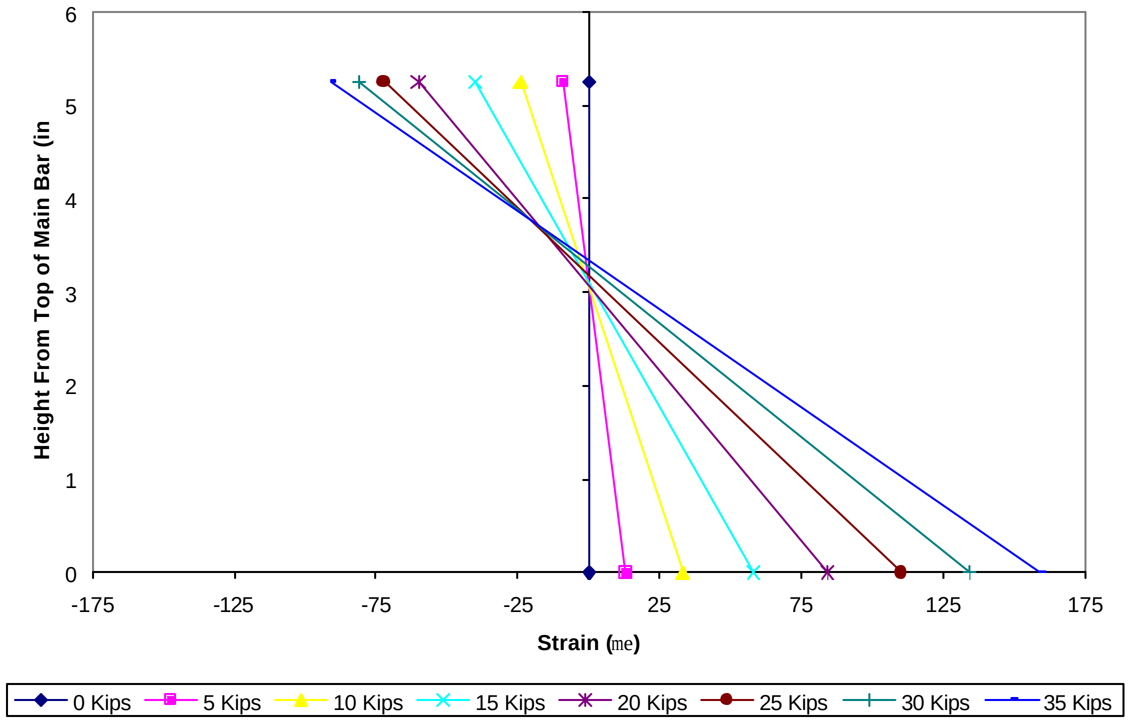

Figure B-164 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-2100K Cycles

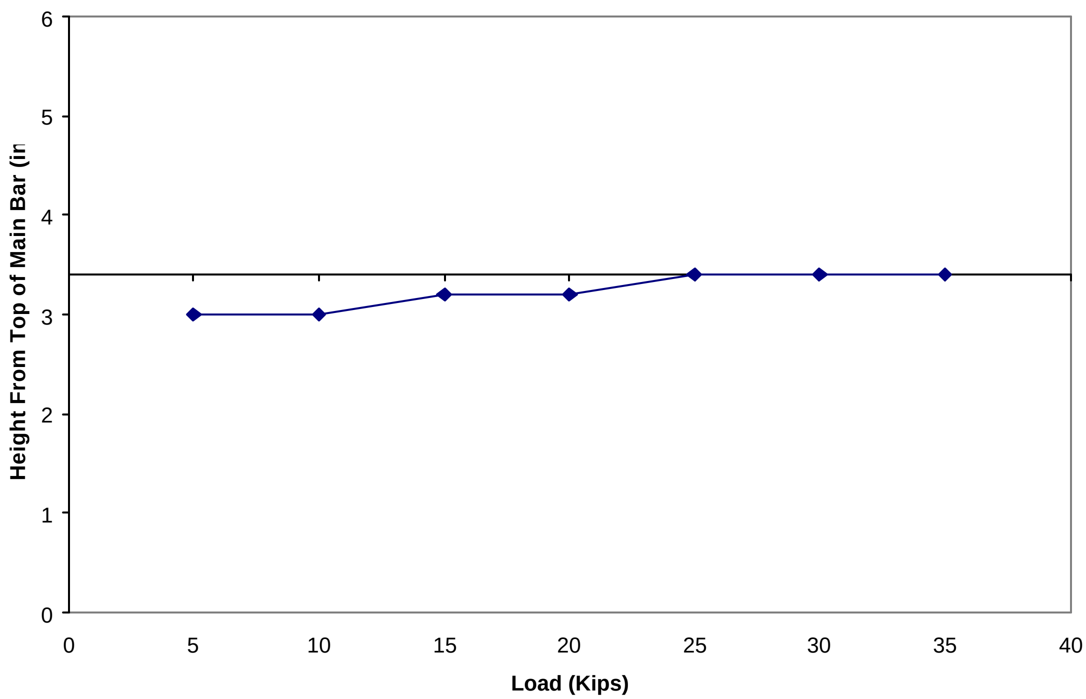

Figure B-165 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-2100K Cycles

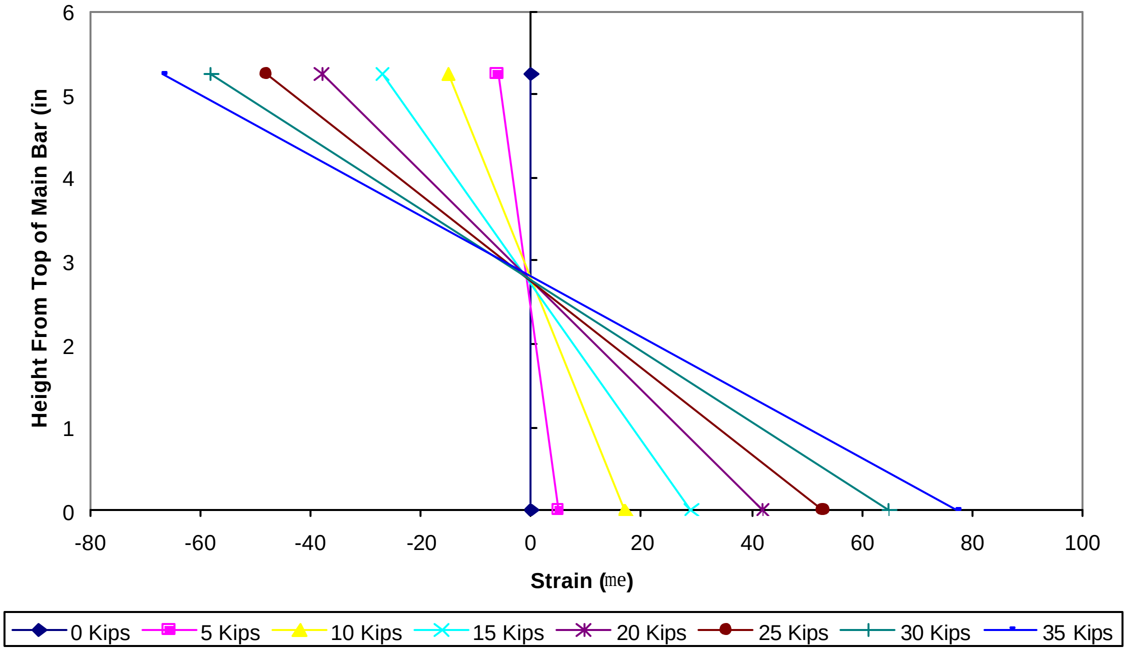

Figure B-166 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-2250K Cycles

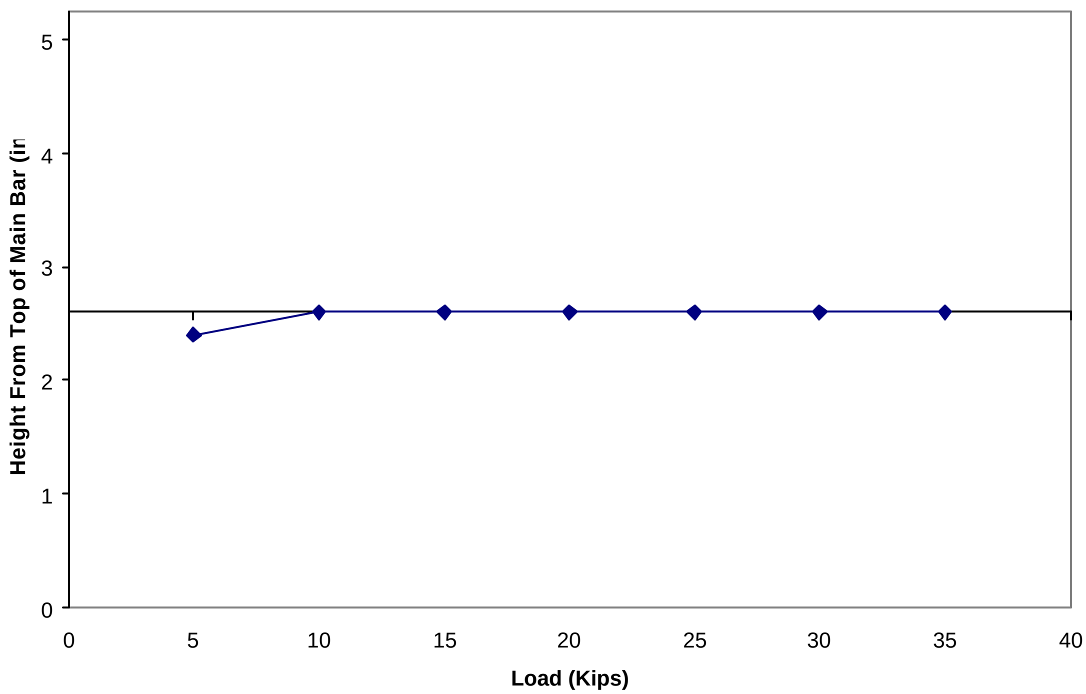

Figure B-167 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-2250K Cycles

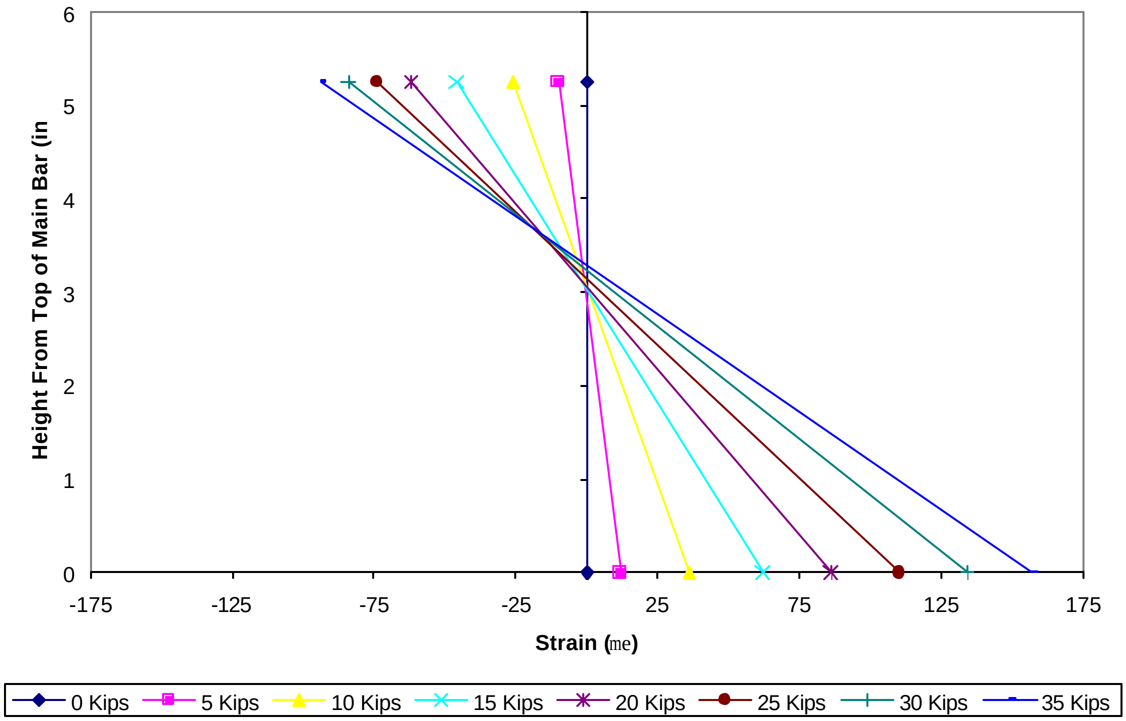

Figure B-168 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-2250K Cycles

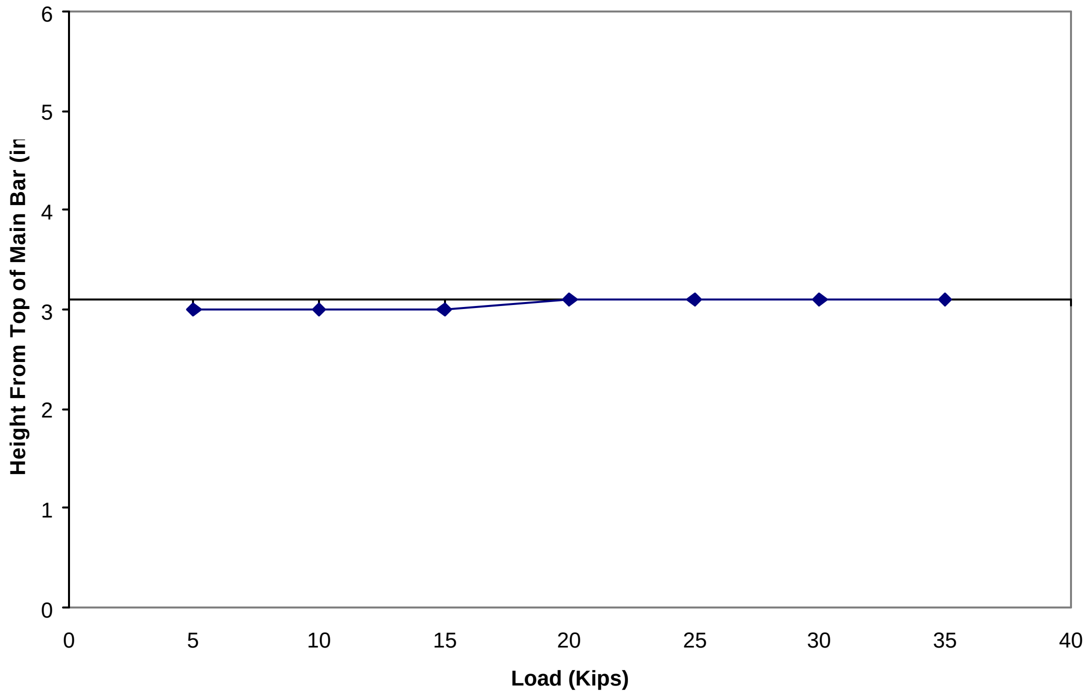

Figure B-169 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-2250K Cycles

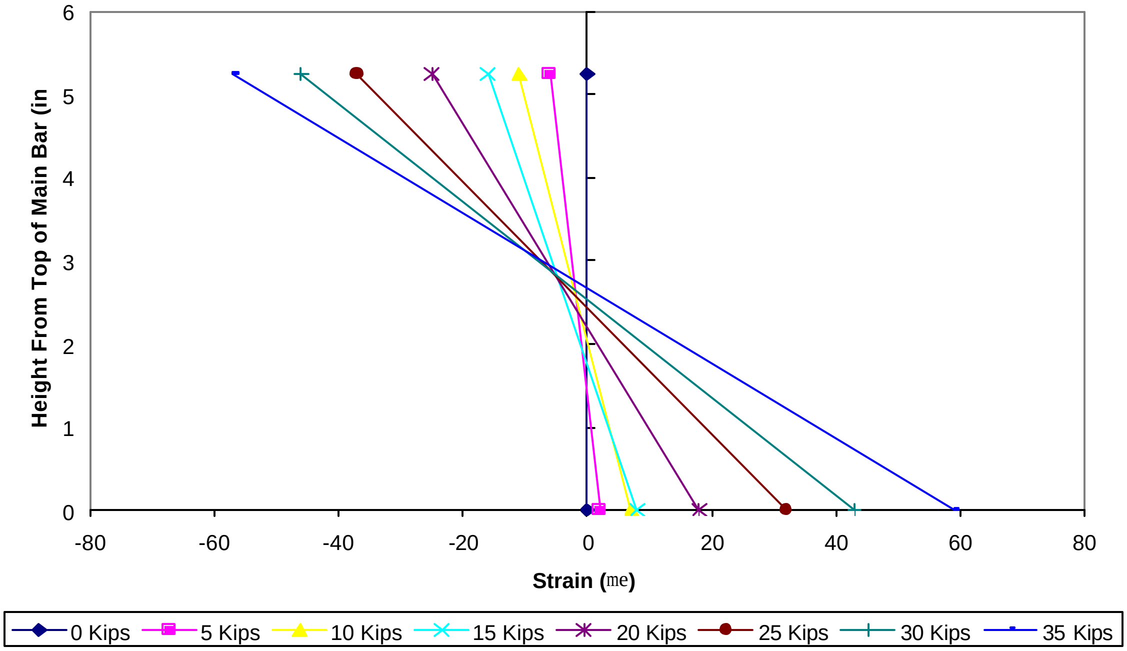

Figure B-170 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-2400K Cycles

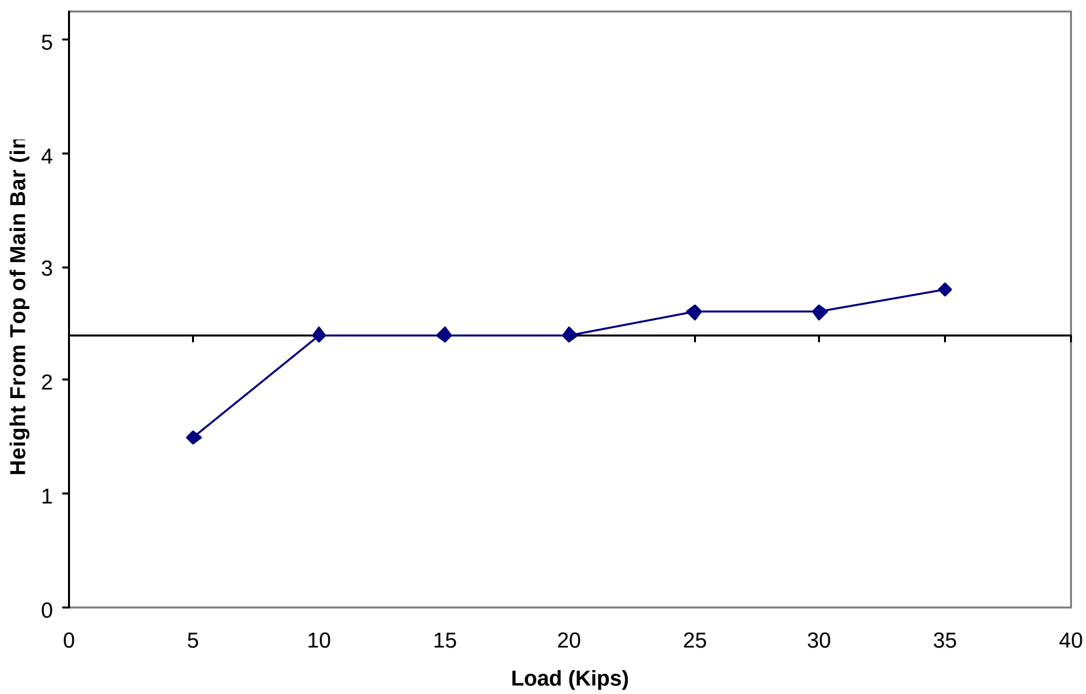

Figure B-171 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-2400K Cycles

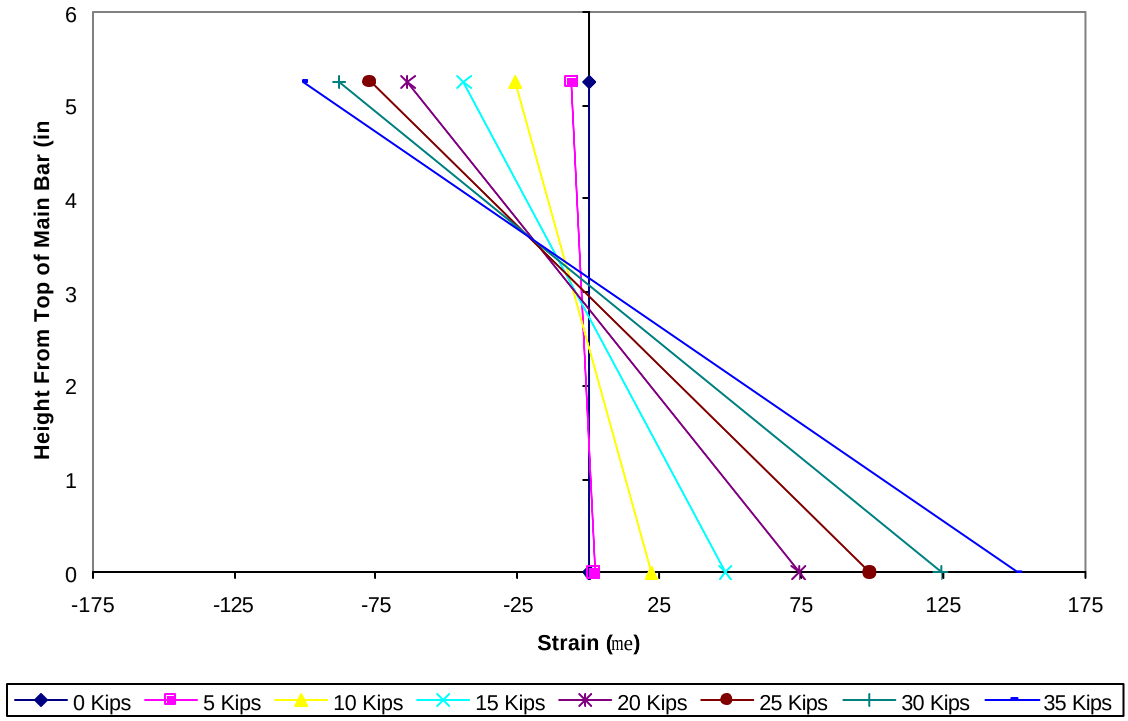

Figure B-172 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-2400K Cycles

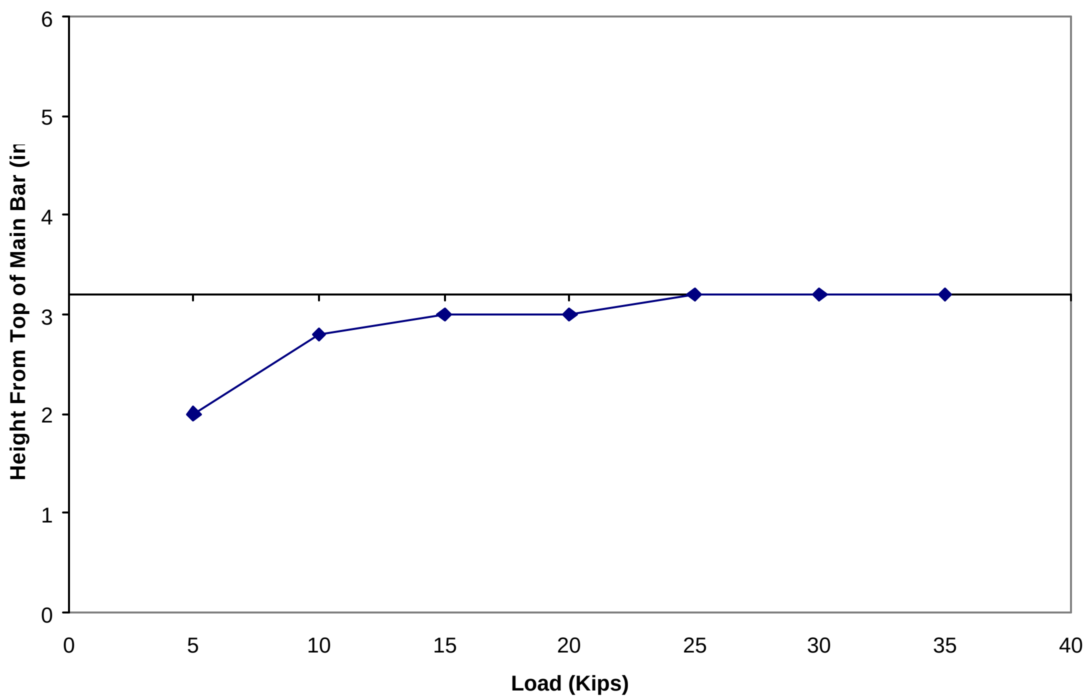

Figure B-173 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-2400K Cycles

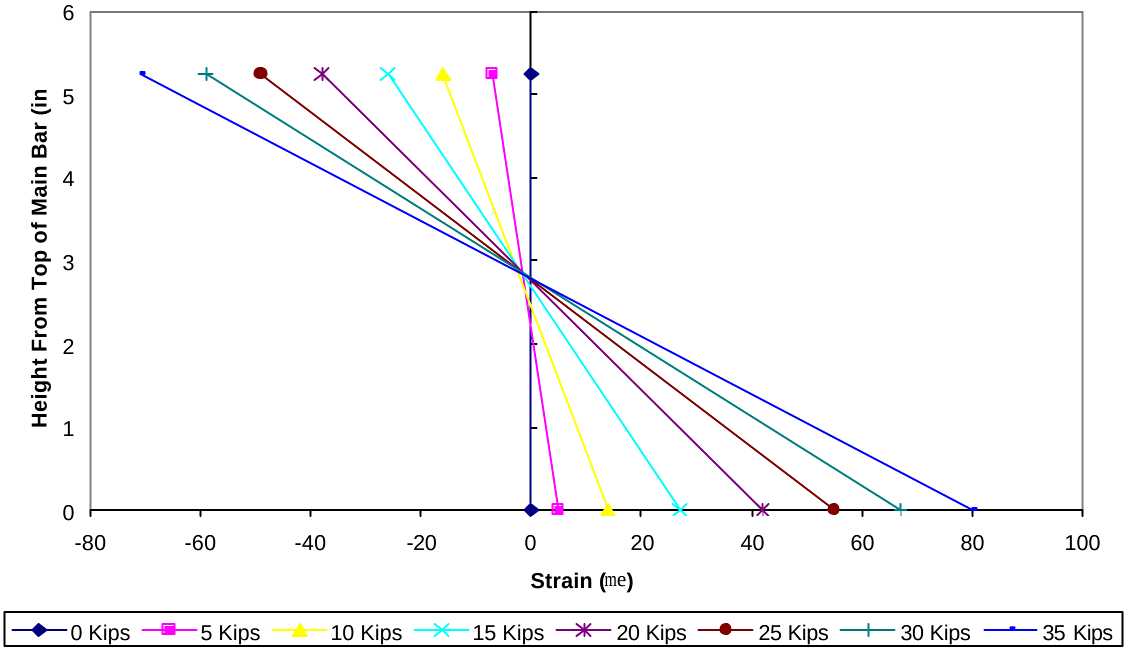

Figure B-174 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-2550K Cycles

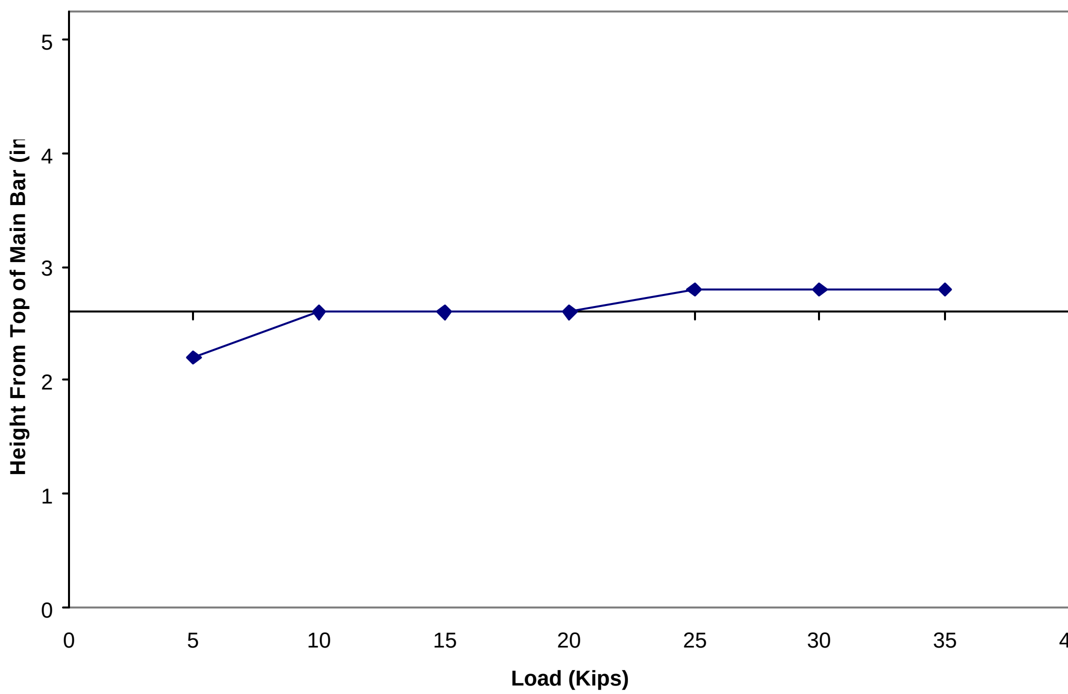

Figure B-175 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-2550K Cycles

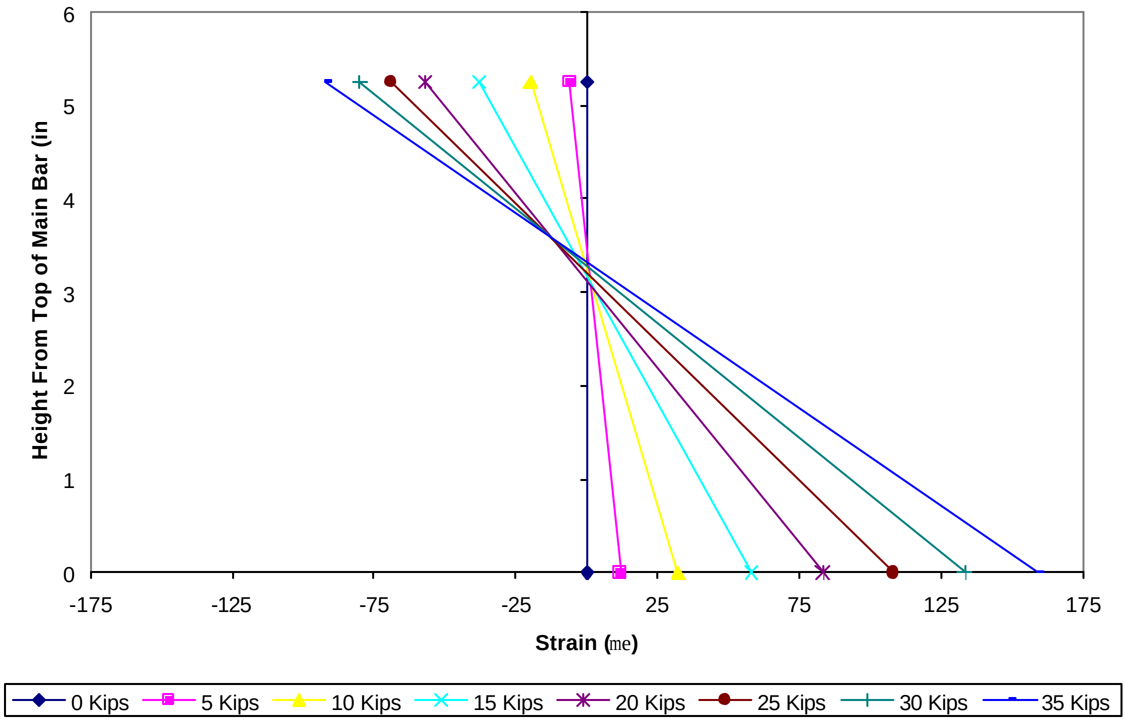

Figure B-176 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-2550K Cycles

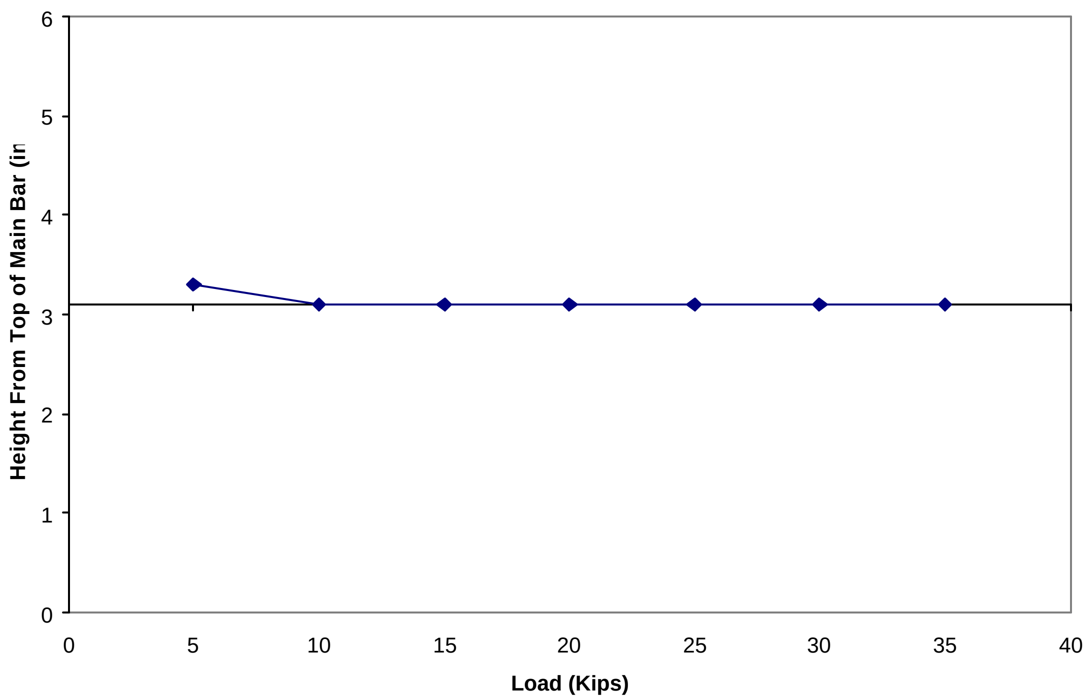

Figure B-177 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-2550K Cycles

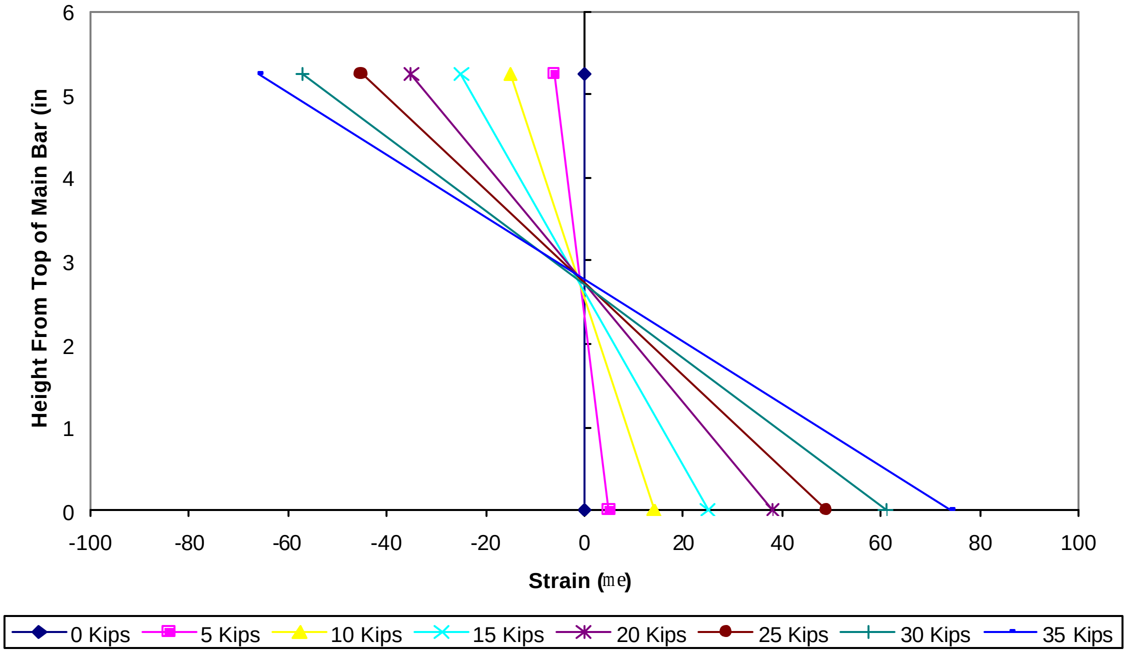

Figure B-178 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-2700K Cycles

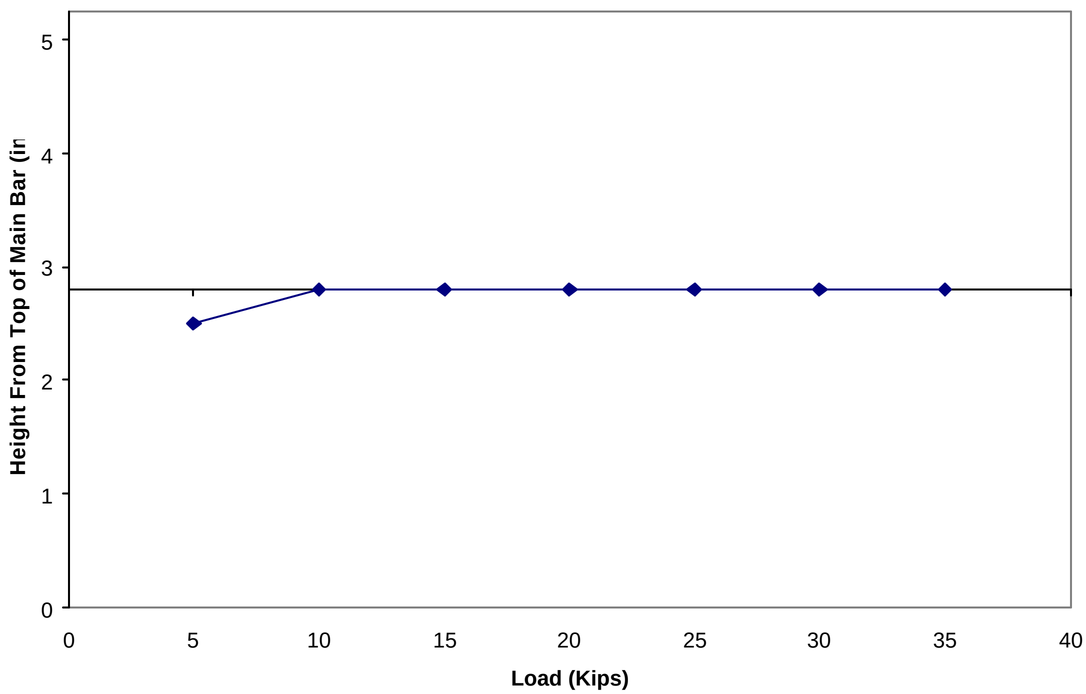

Figure B-179 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-2700K Cycles

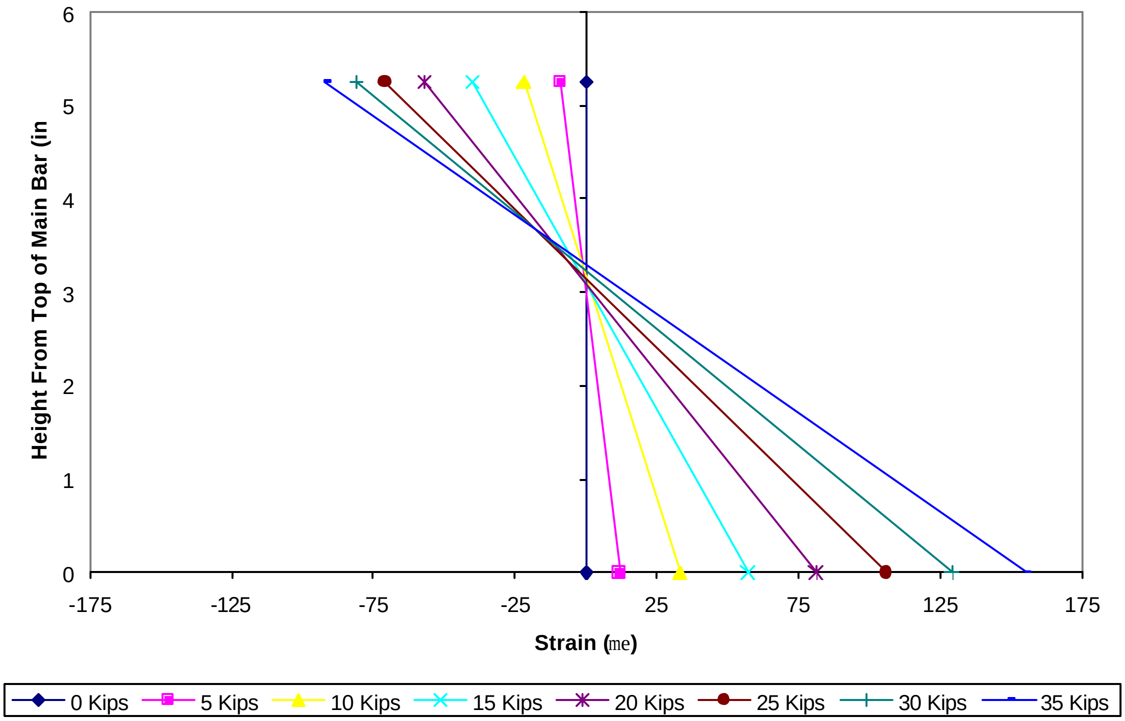

Figure B-180 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-2700K Cycles

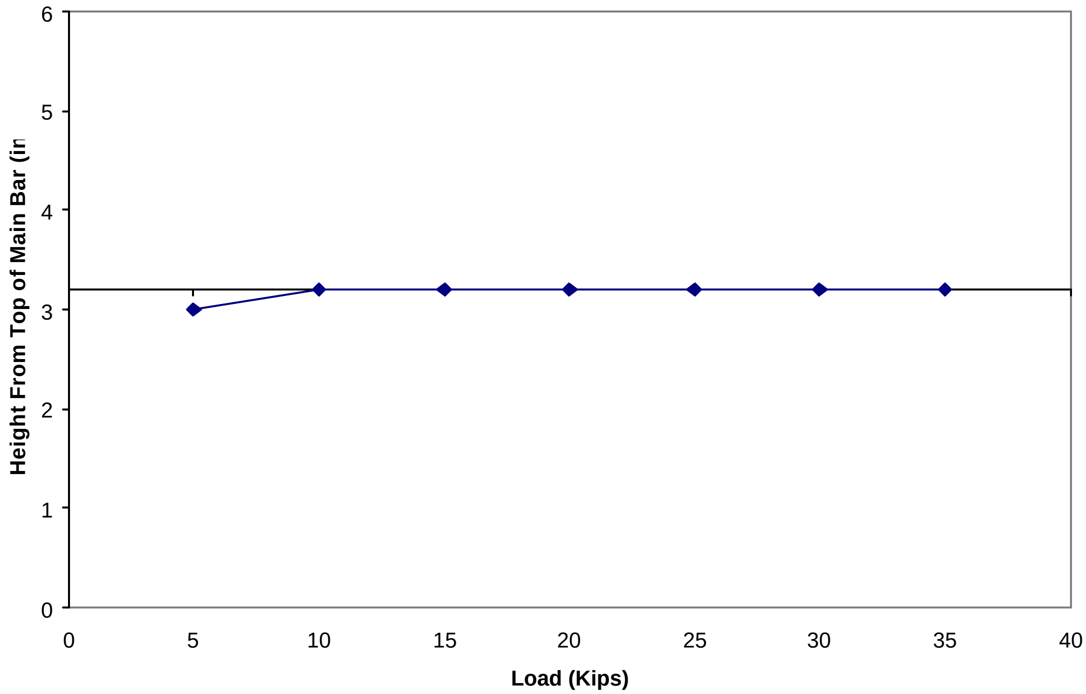

Figure B-181 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-2700K Cycles

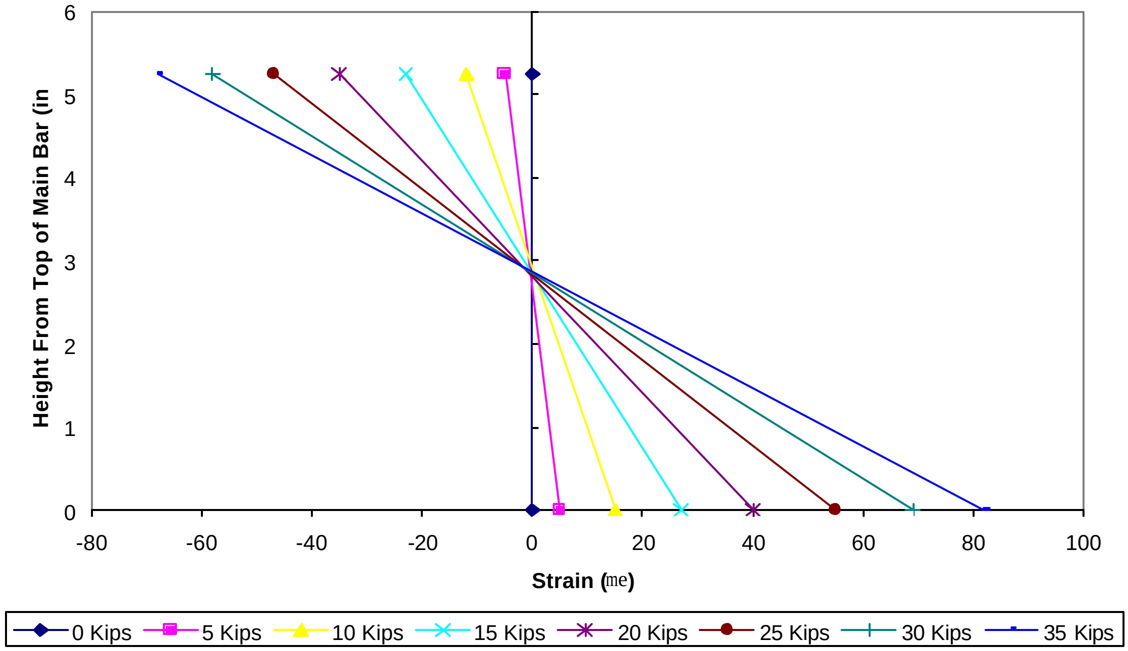

Figure B-182 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-2850K Cycles

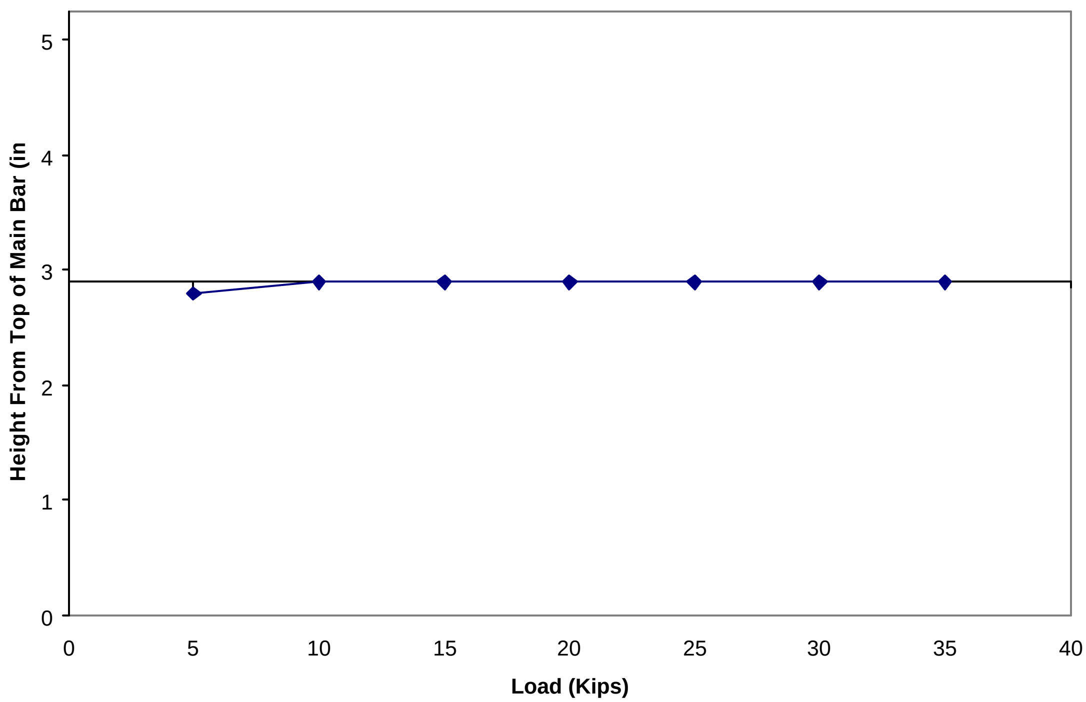

Figure B-183 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-2850K Cycles

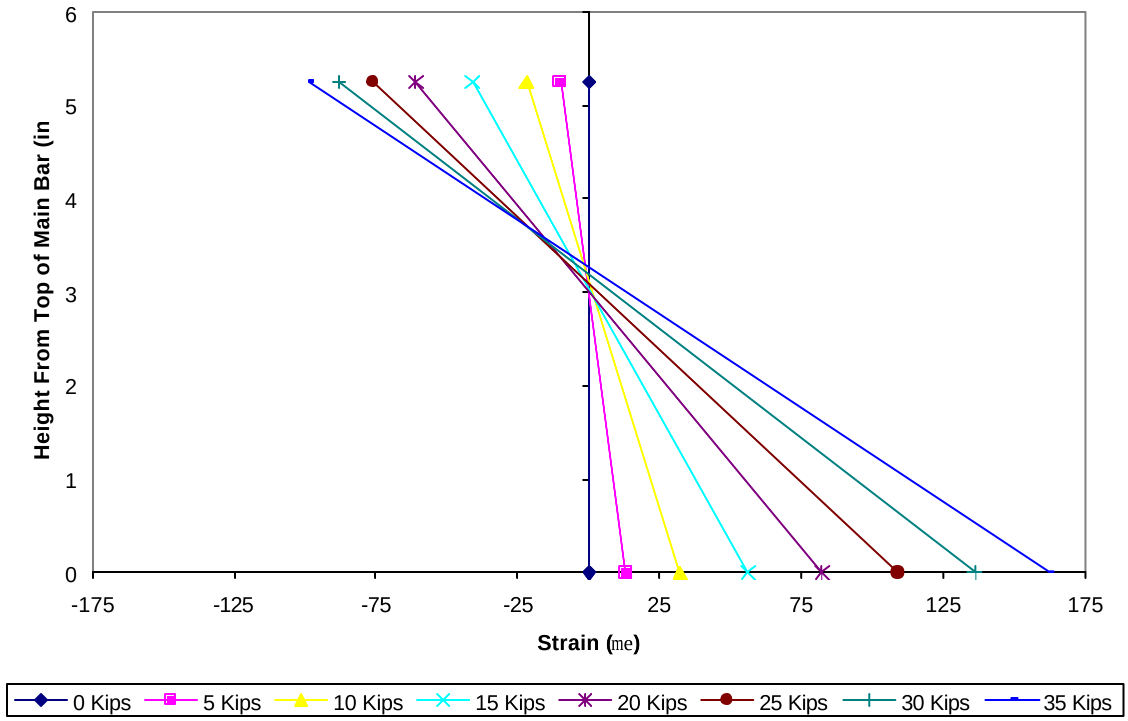

Figure B-184 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-2850K Cycles

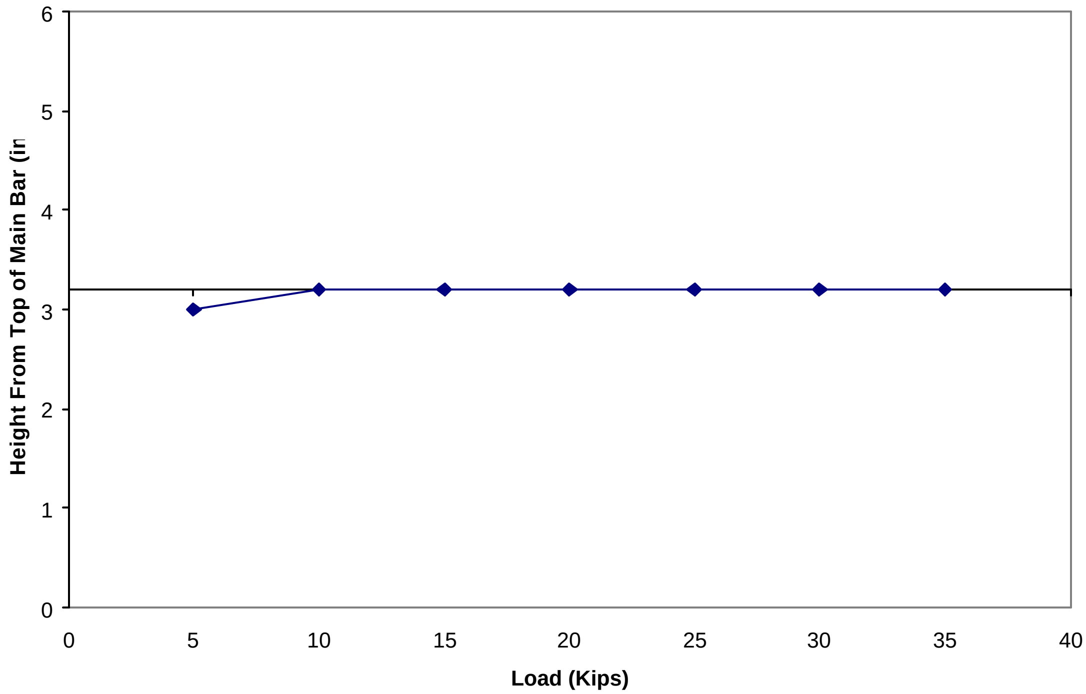

Figure B-185 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-2850K Cycles

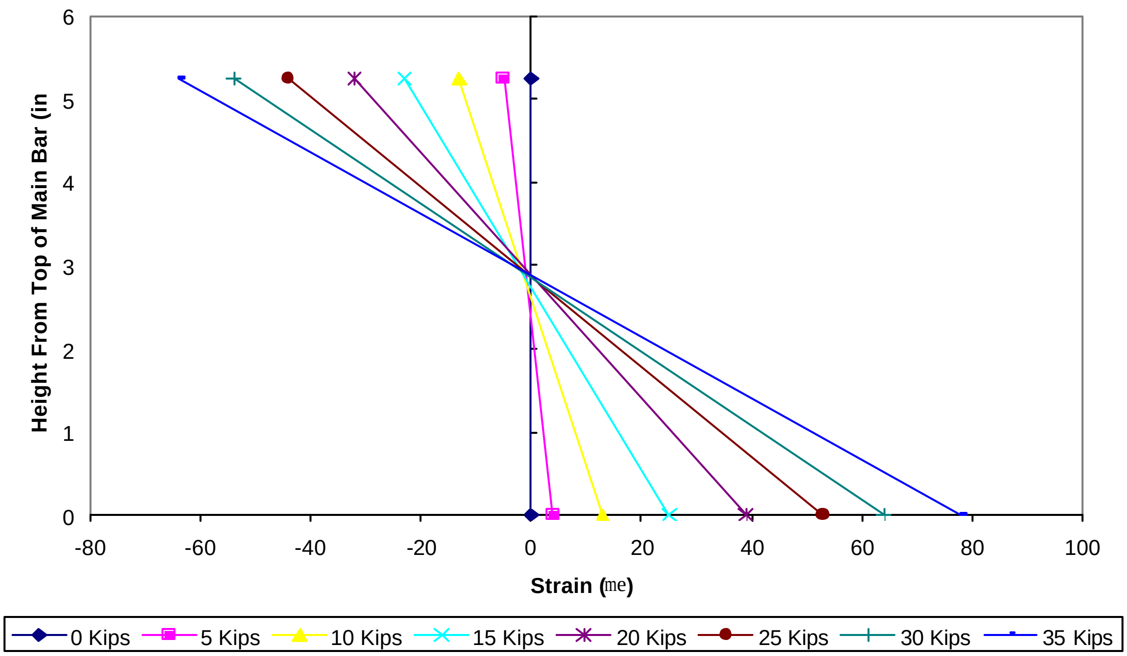

Figure B-186 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-3000K Cycles

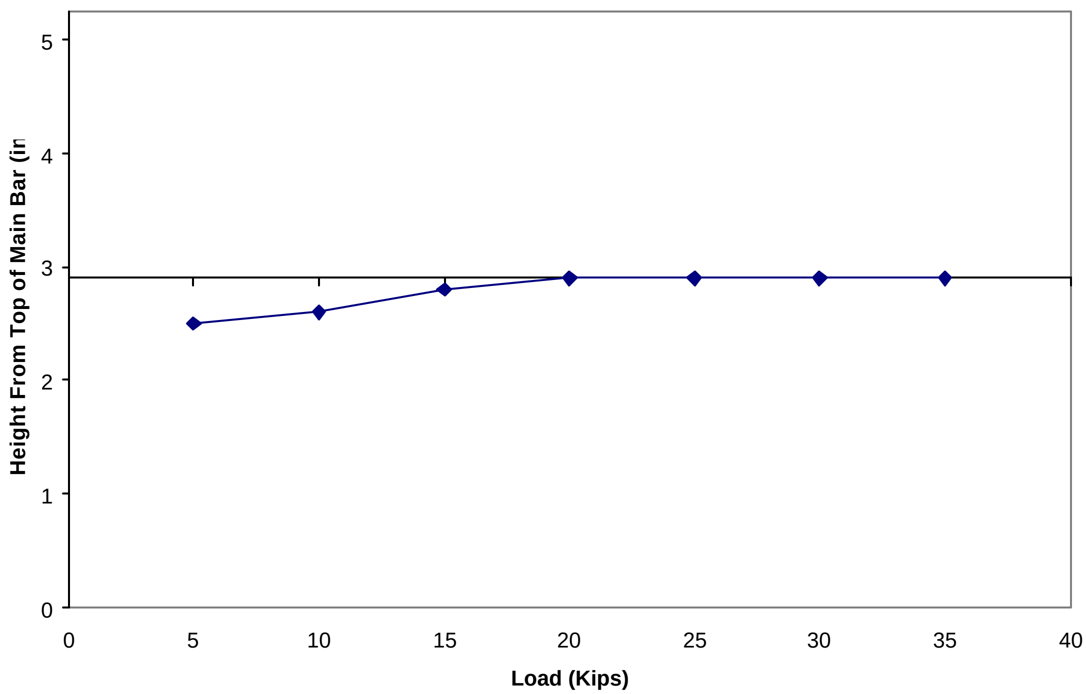

Figure B-187 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-3000K Cycles

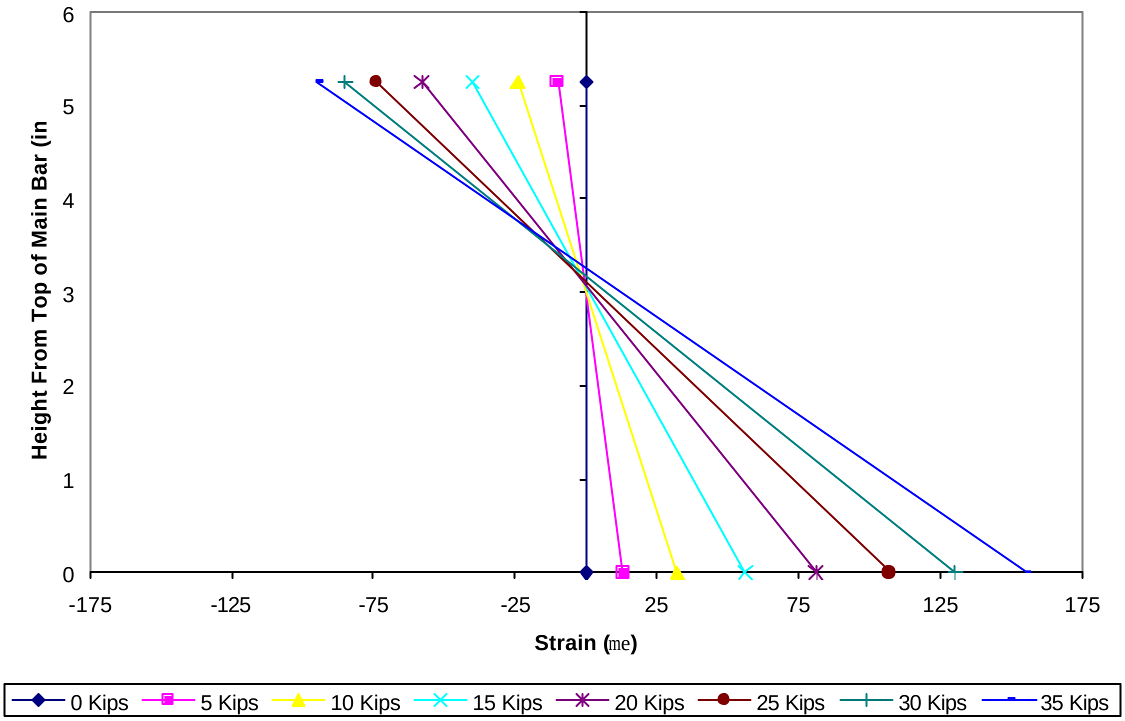

Figure B-188 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-3000K Cycles

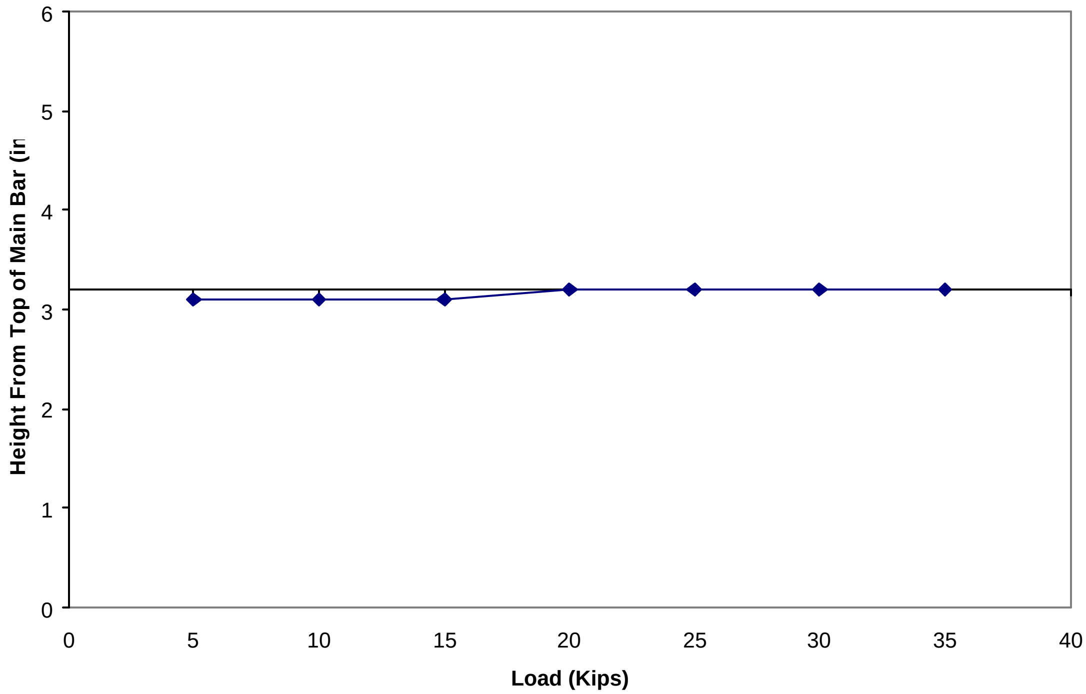

Figure B-189 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-3000K Cycles

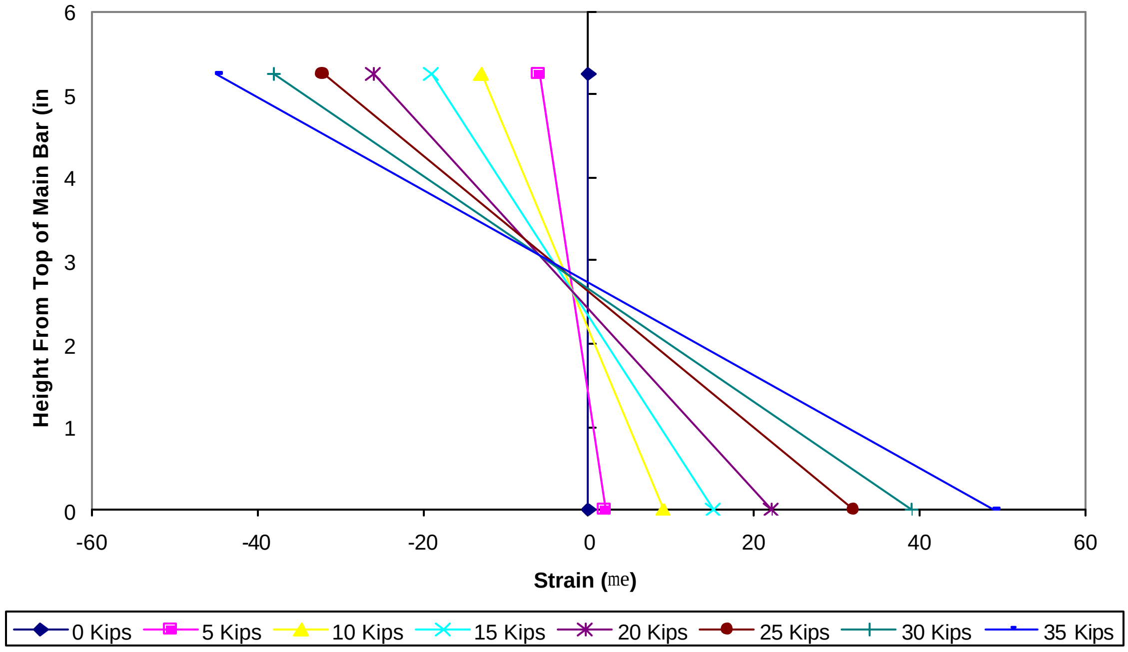

Figure B-190 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-3150K Cycles

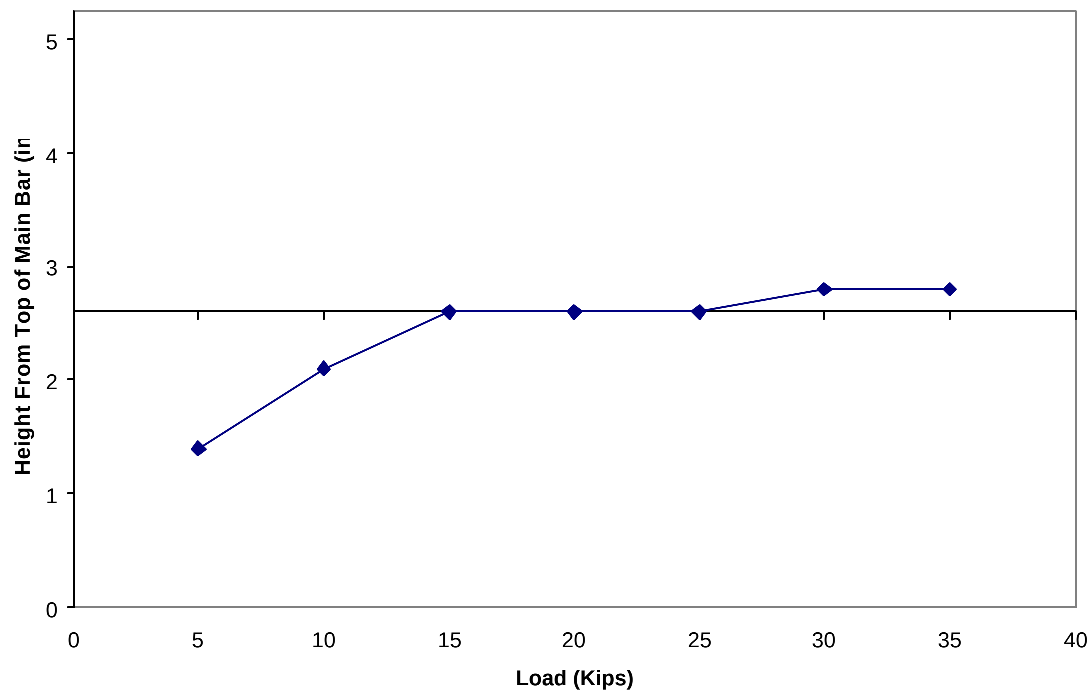

Figure B-191 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-3150K Cycles

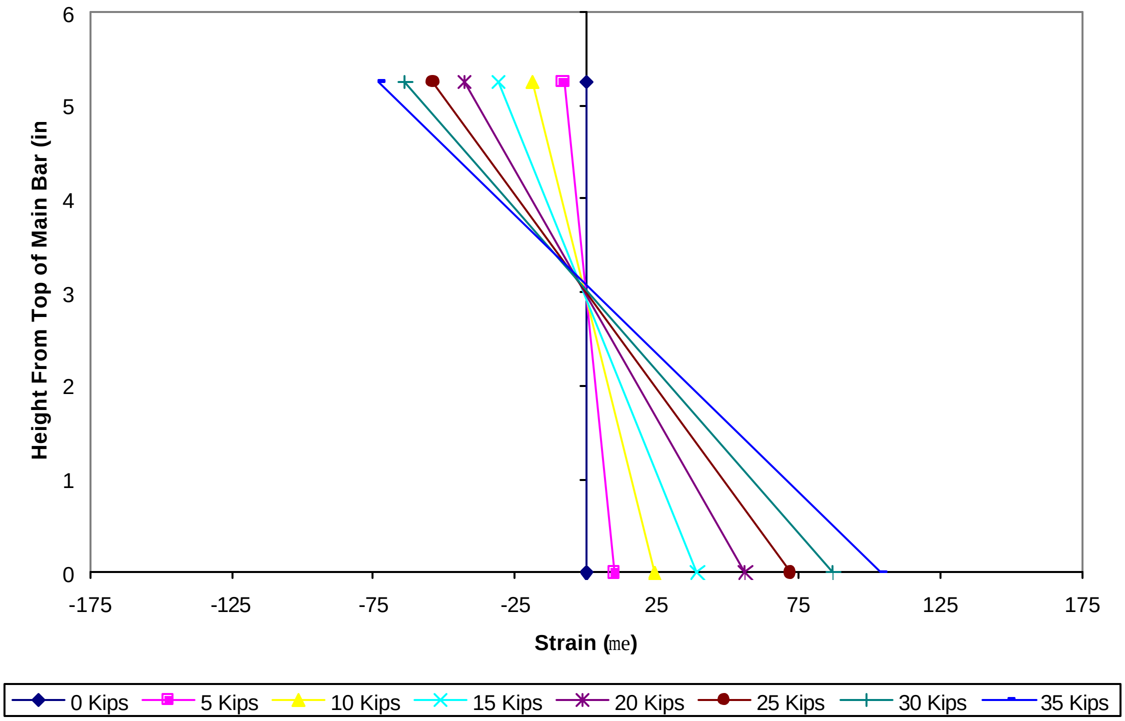

Figure B-192 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-3150K Cycles

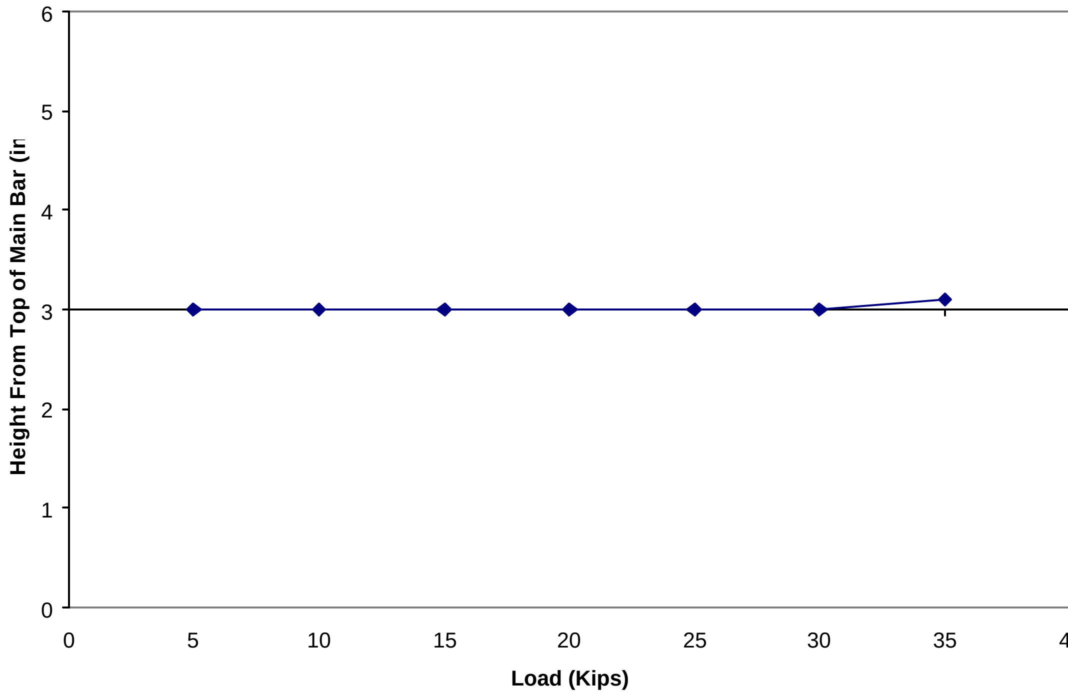

Figure B-193 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-3150K Cycles

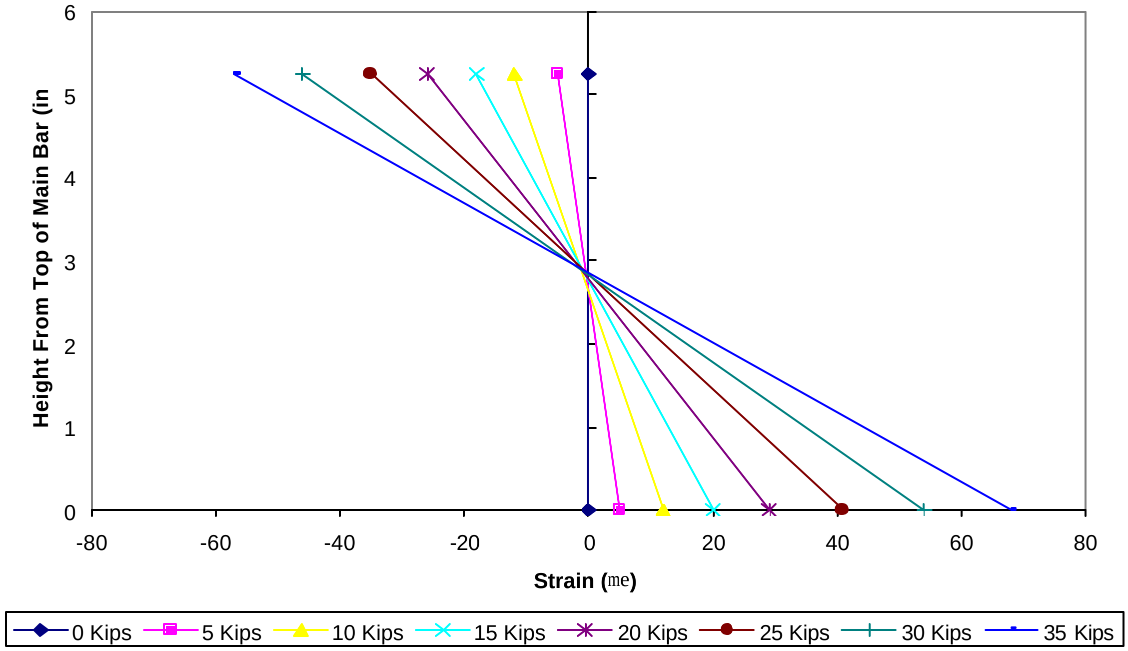

Figure B-194 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-3300K Cycles

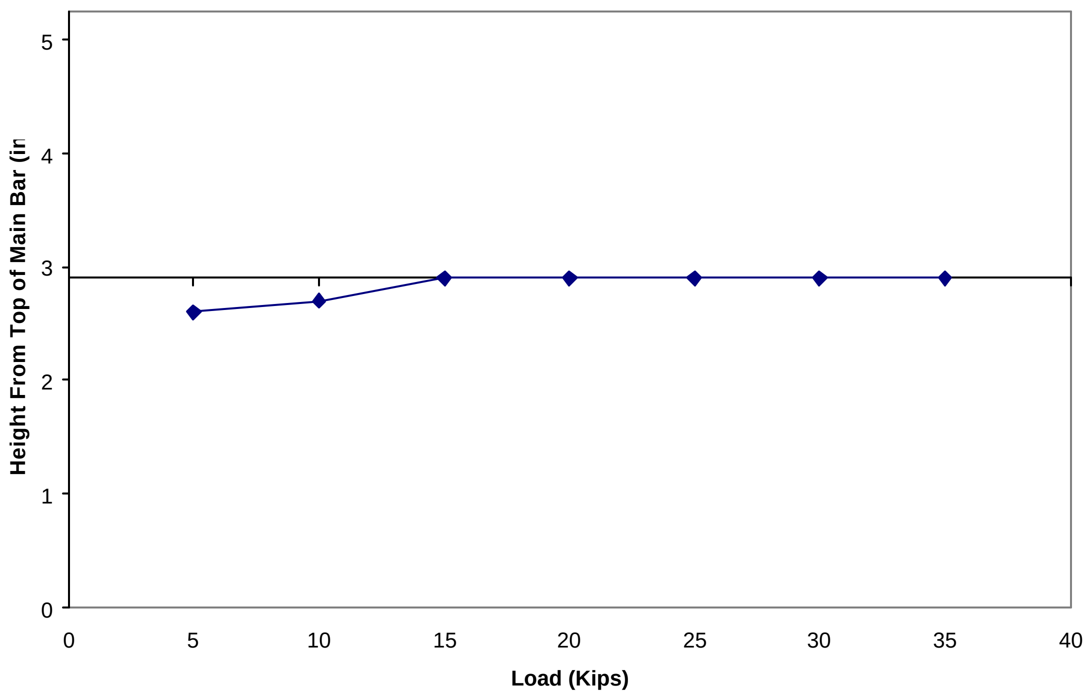

Figure B-195 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-3300K Cycles

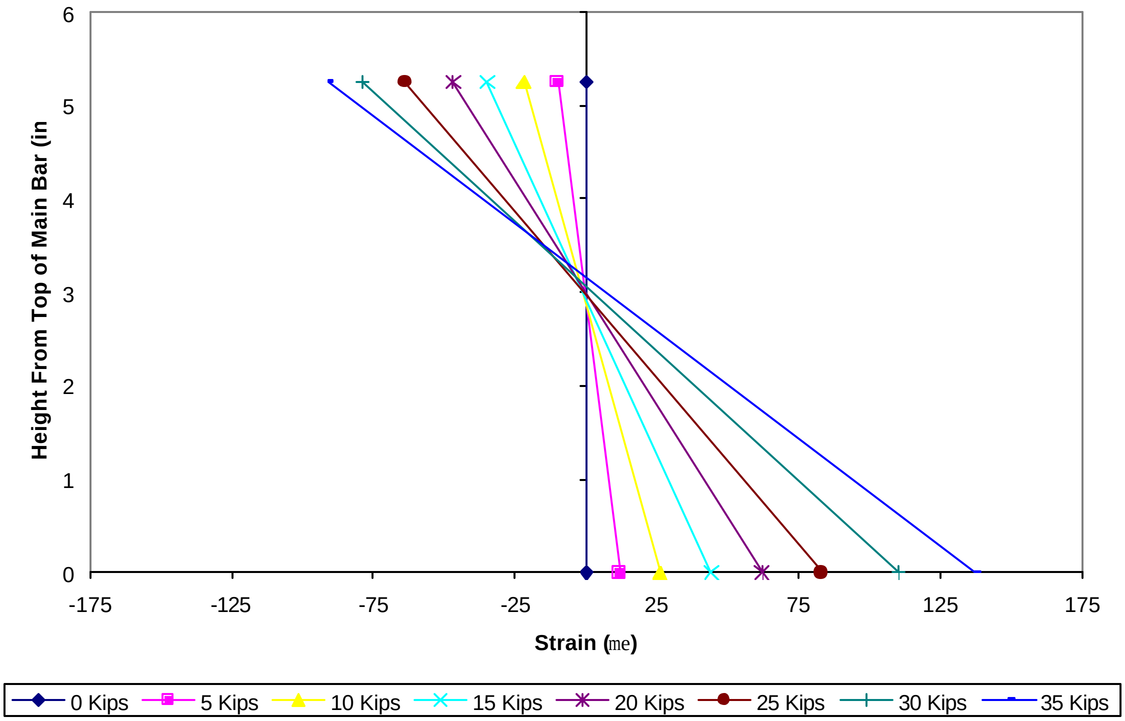

Figure B-196 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-3300K Cycles

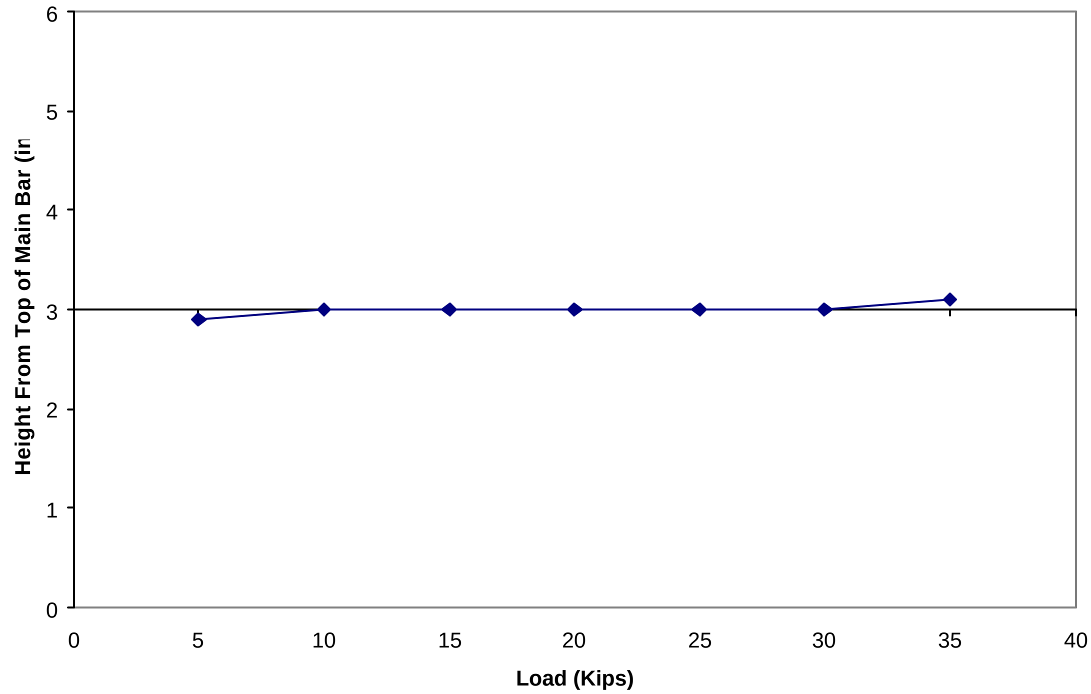

Figure B-197 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-3300K Cycles

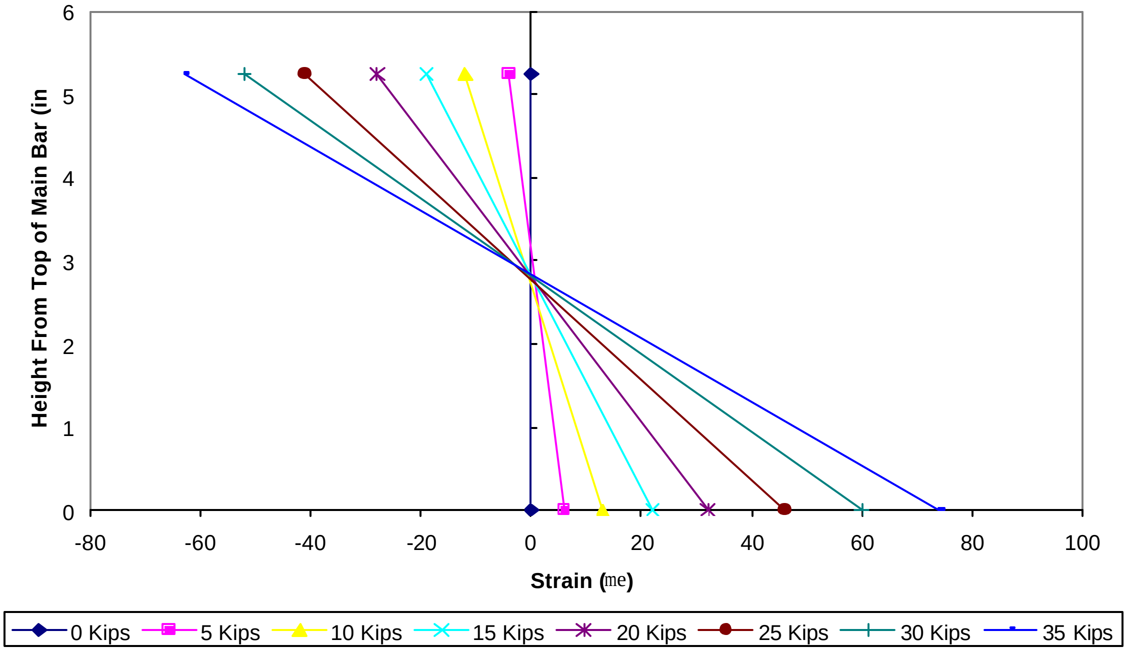

Figure B-198 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-3450K Cycles

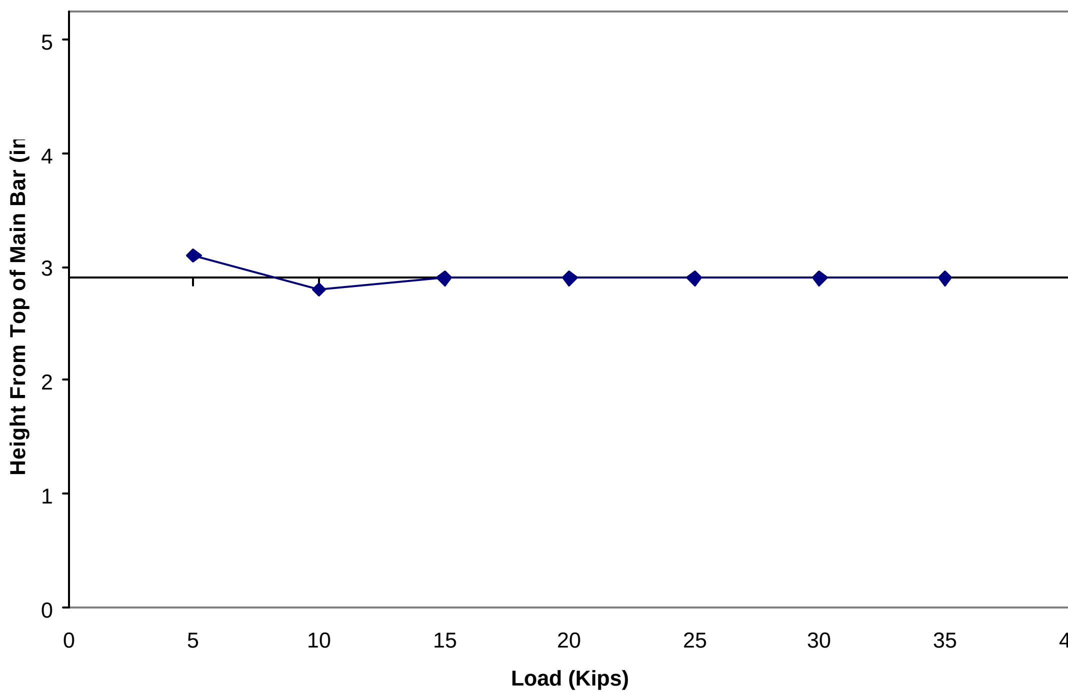

Figure B-199 Fatigue Specimen #1 Main Bar #1
-Neutral Axis Location-3450K Cycles

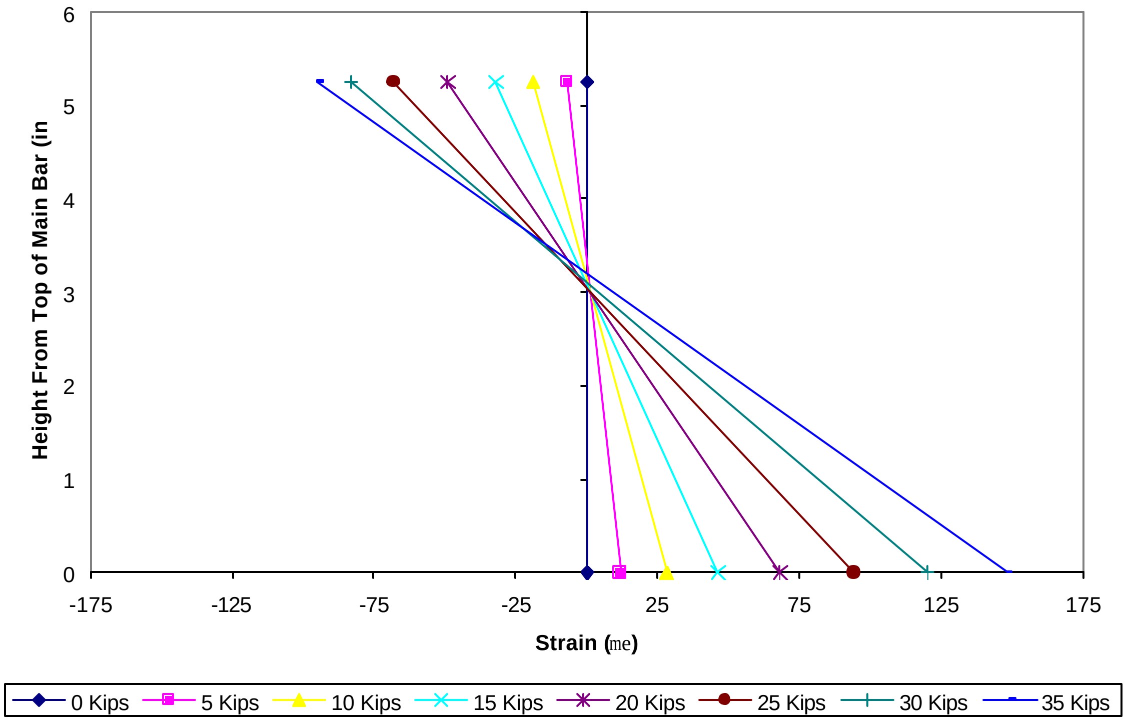

Figure B-200 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-3450K Cycles

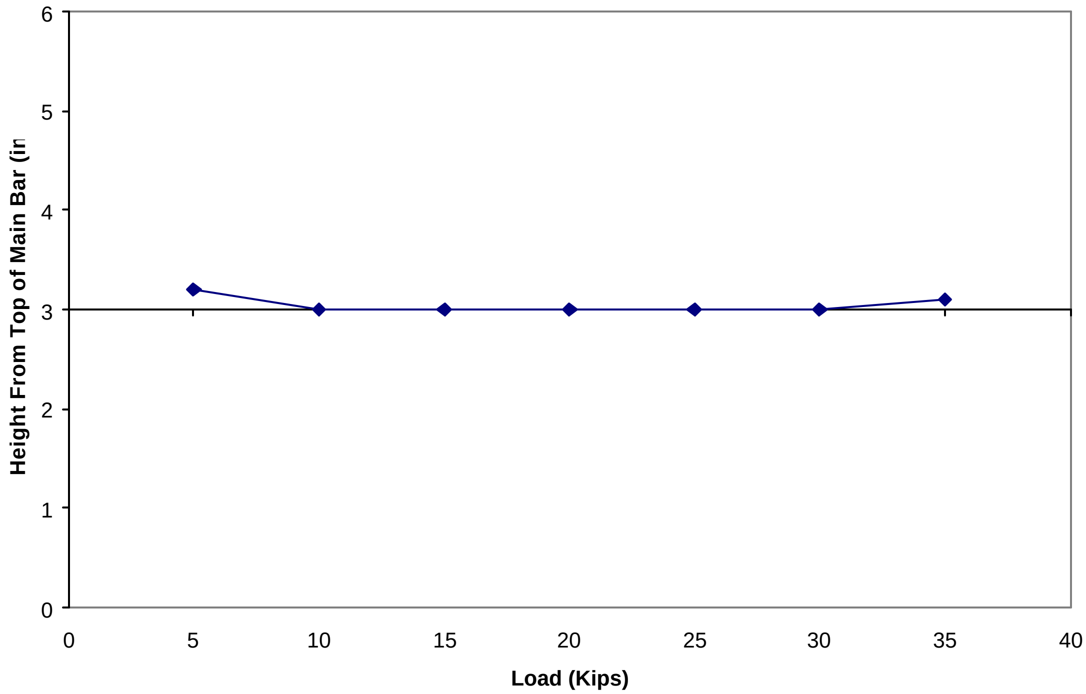

Figure B-201 Fatigue Specimen #1 Main Bar #2
-Neutral Axis Location-3450K Cycles

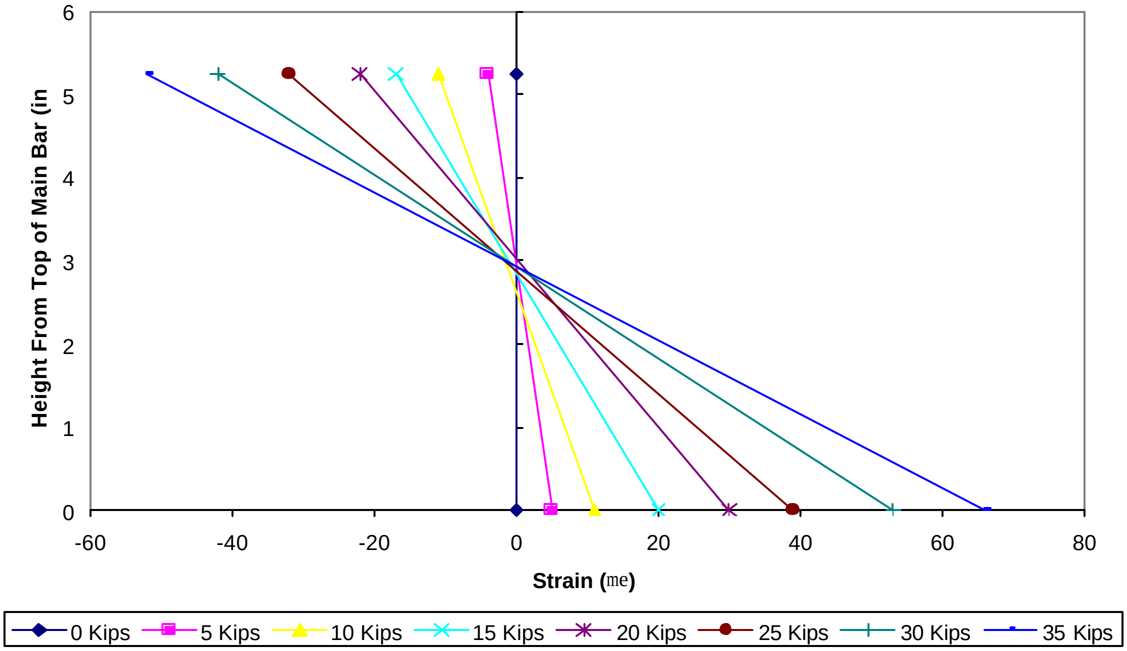

Figure B-202 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-3600K Cycles

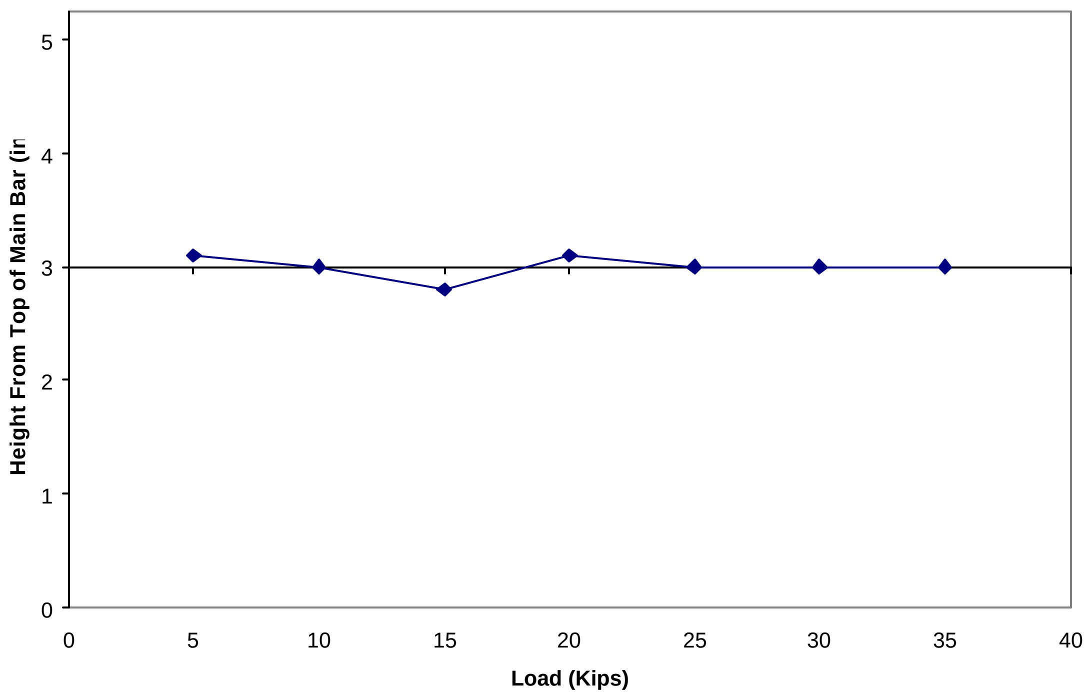

Figure B-203 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-3600K Cycles

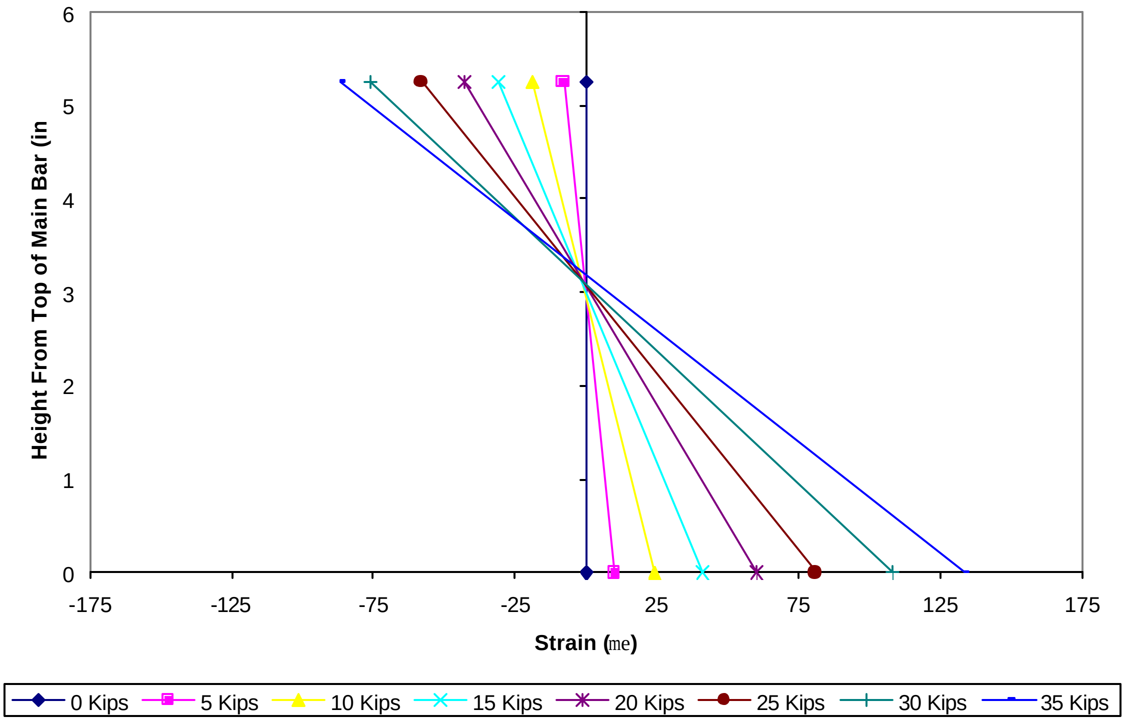

Figure B-204 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-3600K Cycles

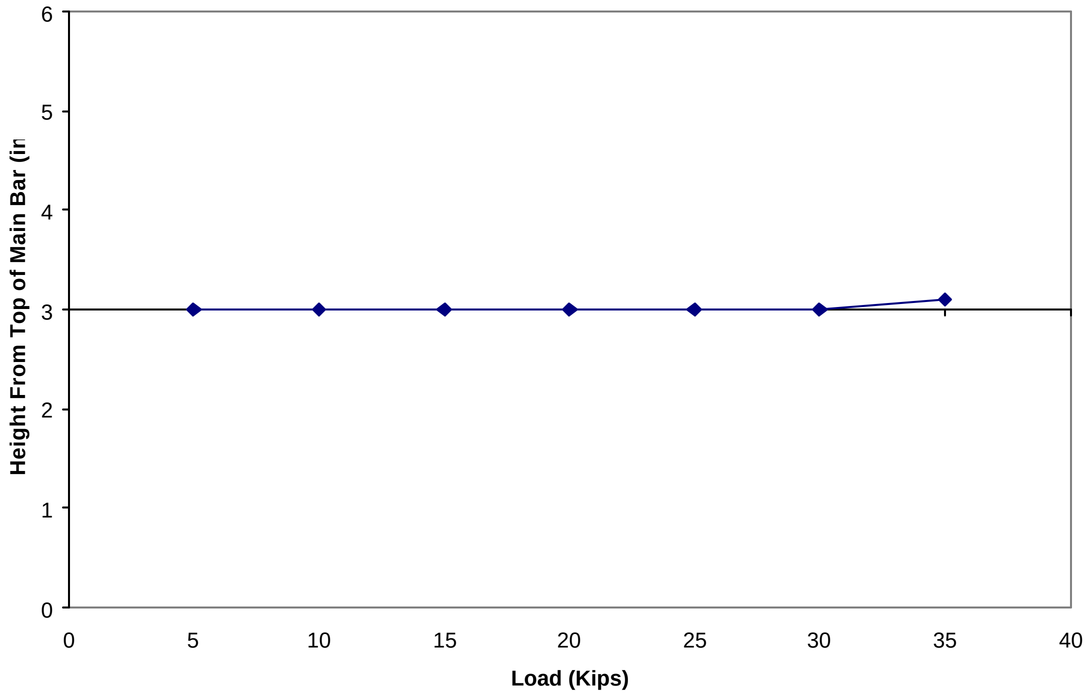

Figure B-205 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-3600K Cycles

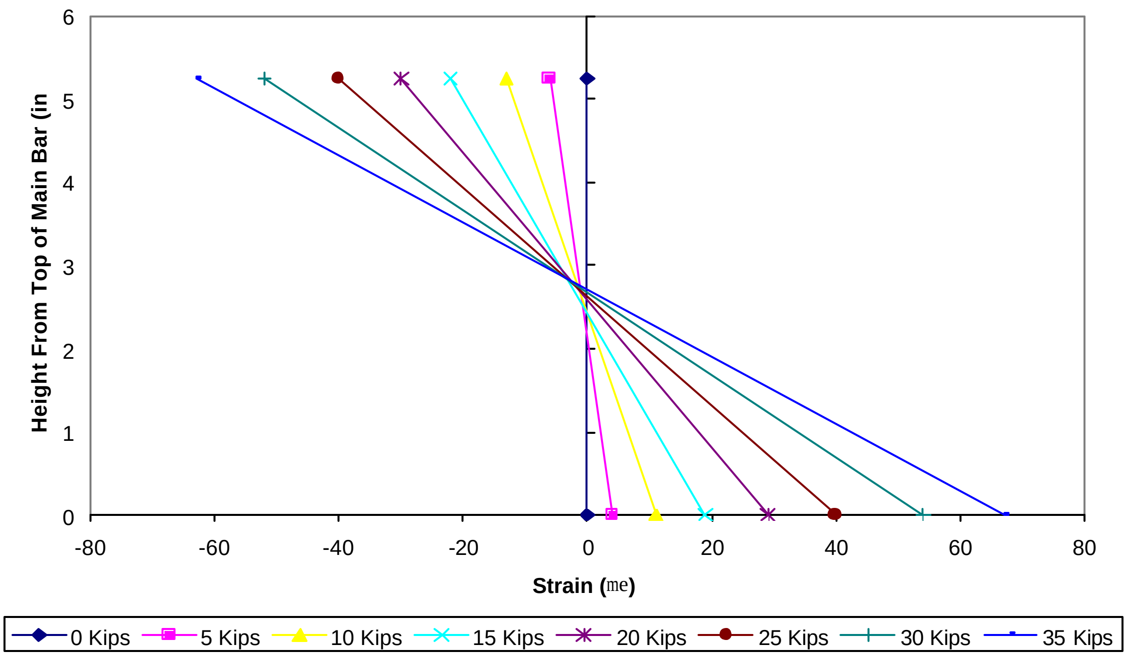

Figure B-206 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-3750K Cycles

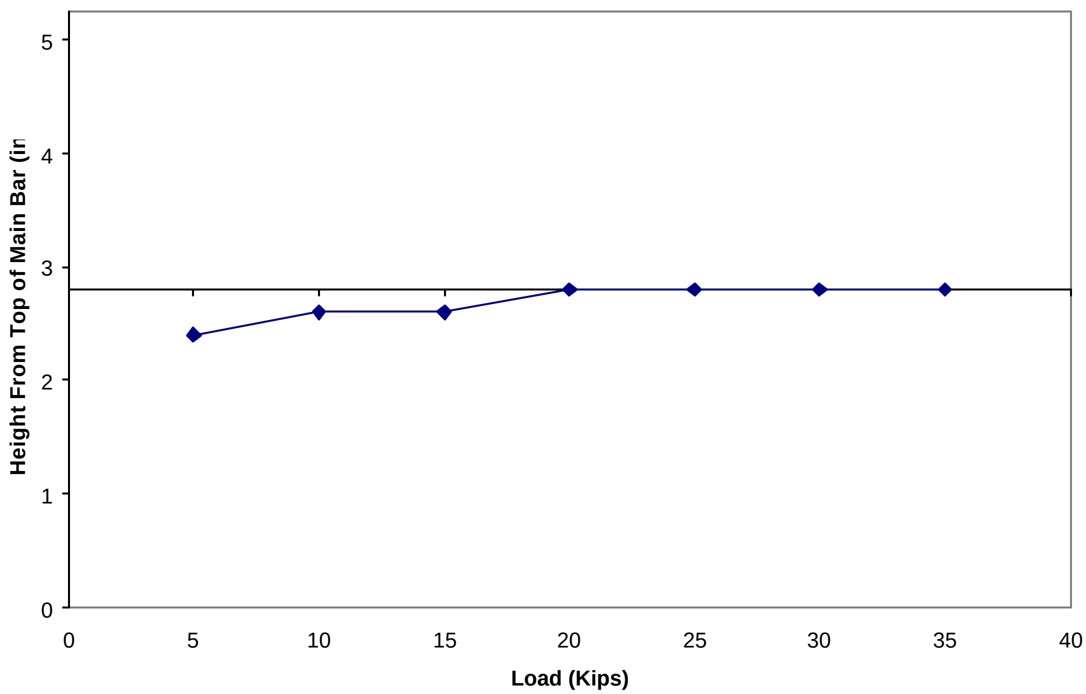

Figure B-207 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-3750K Cycles

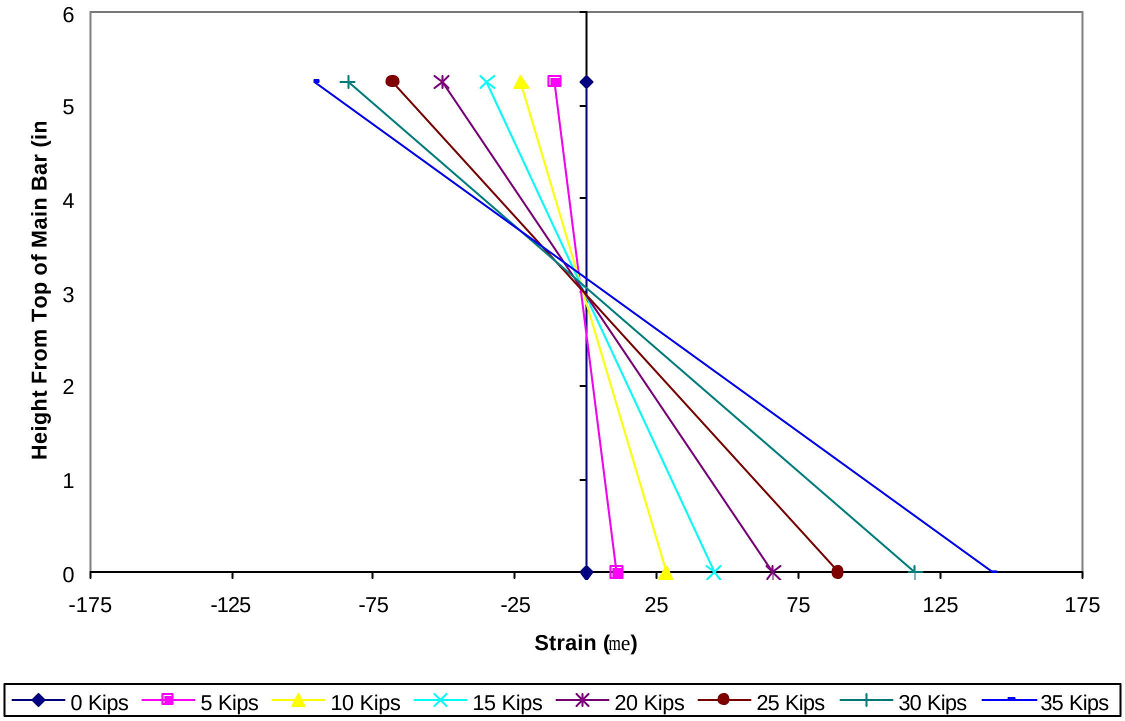

Figure B-208 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-3750K Cycles

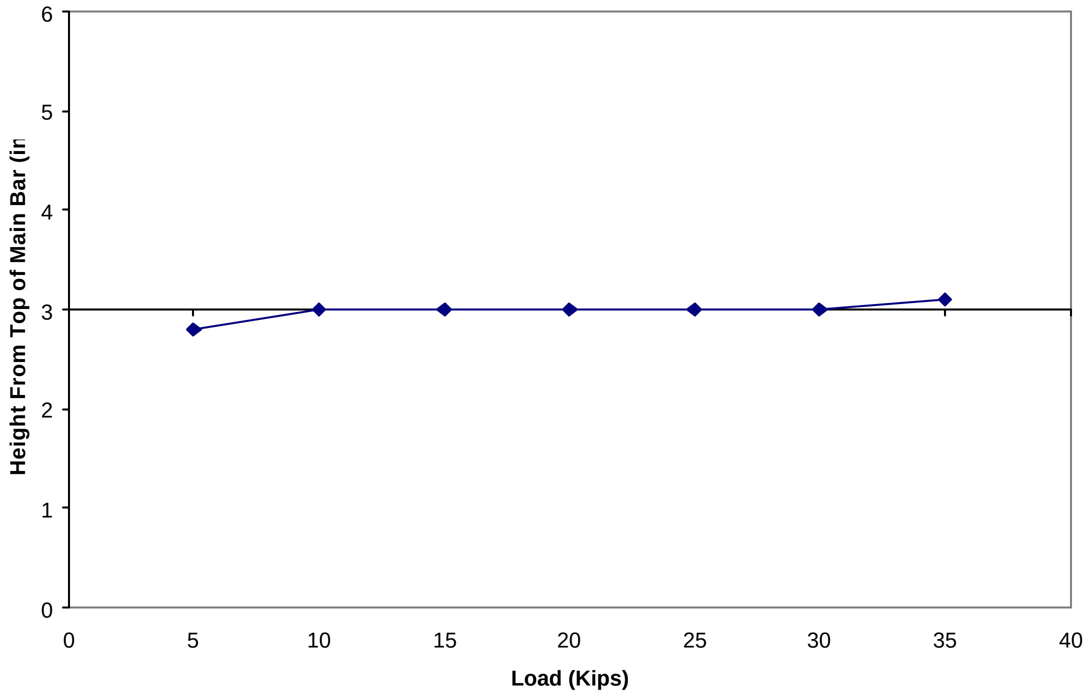

Figure B-209 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-3750K Cycles

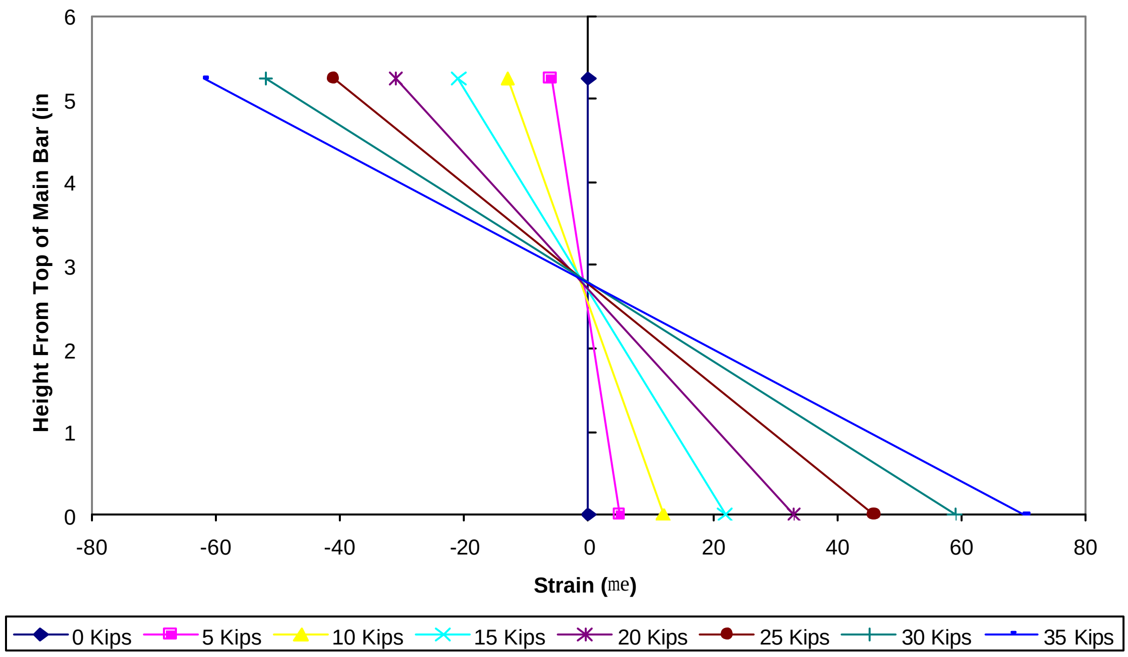

Figure B-210 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-3900K Cycles

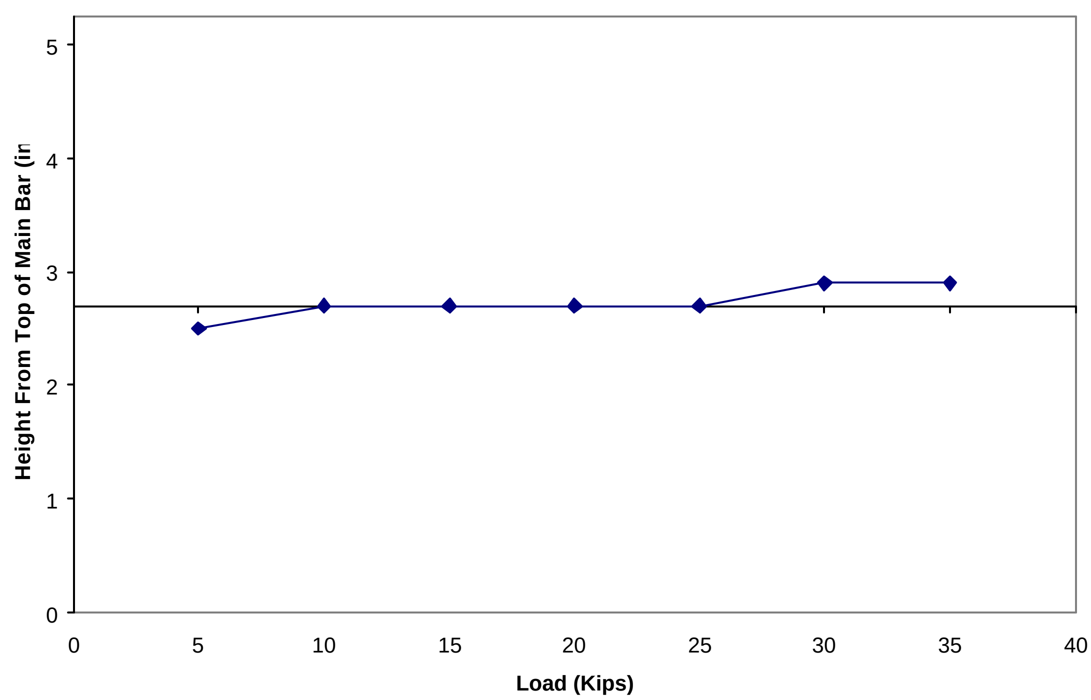

Figure B-211 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-3900K Cycles

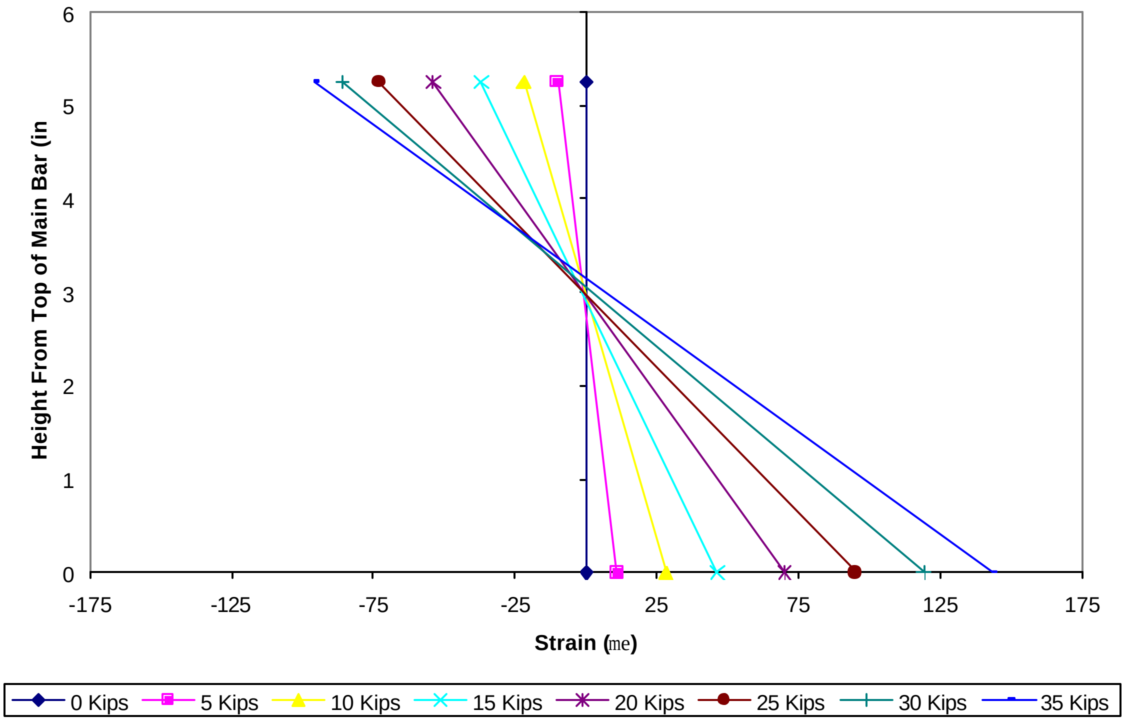

Figure B-212 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-3900K Cycles

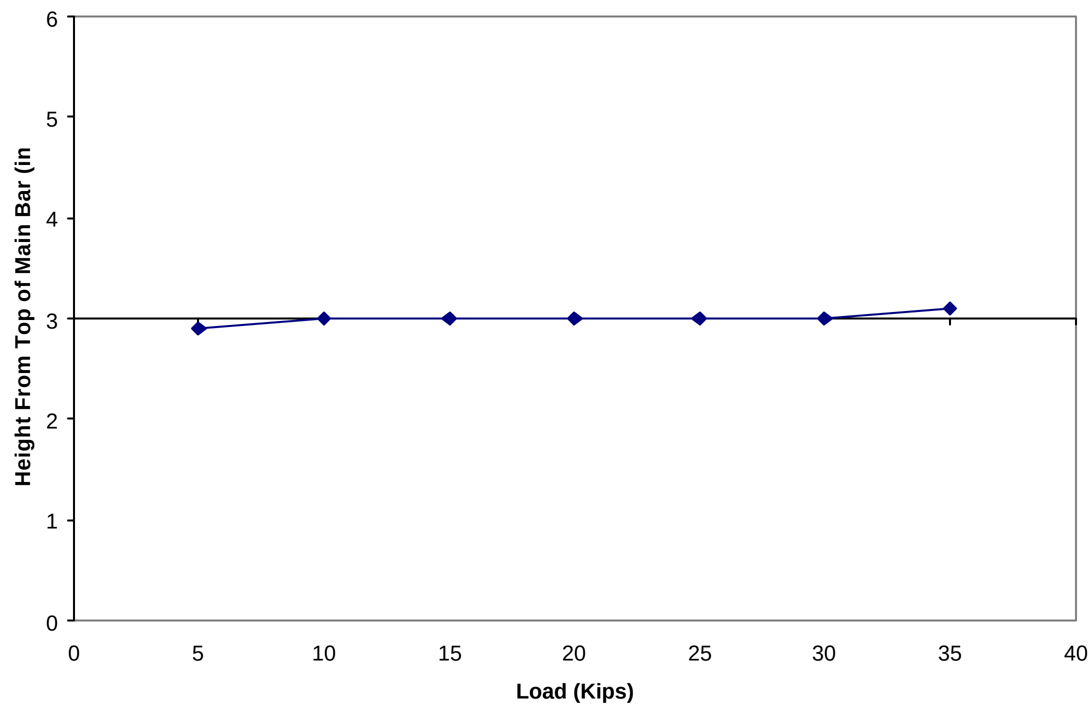

Figure B-213 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-3900K Cycles

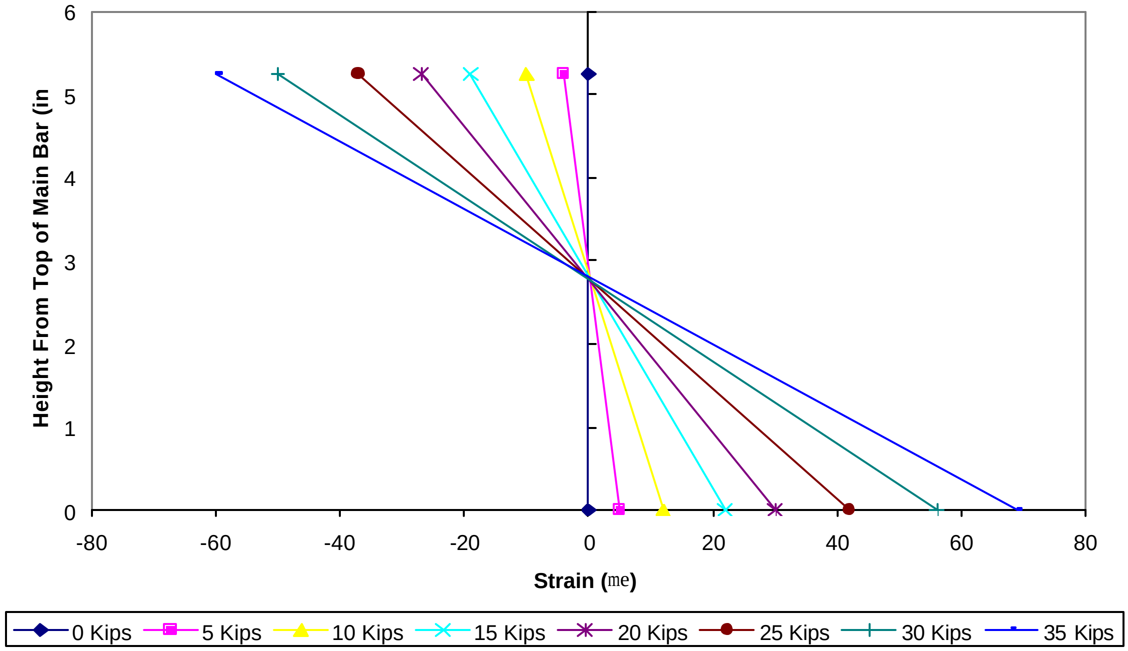

Figure B-214 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-4050K Cycles

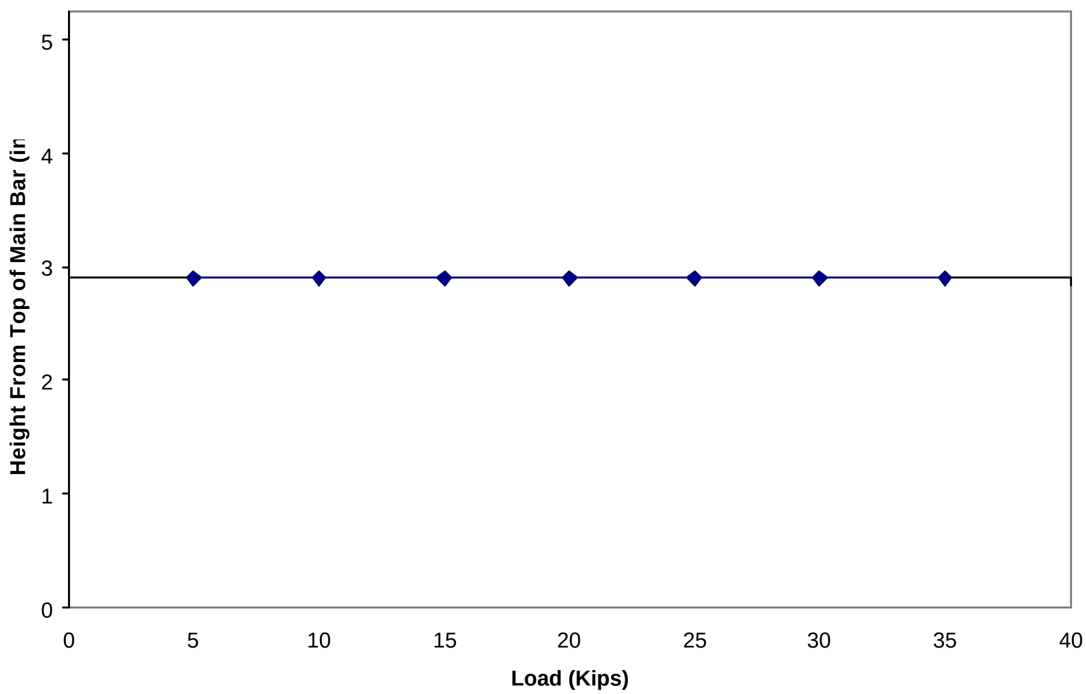

Figure B-215 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-4050K Cycles

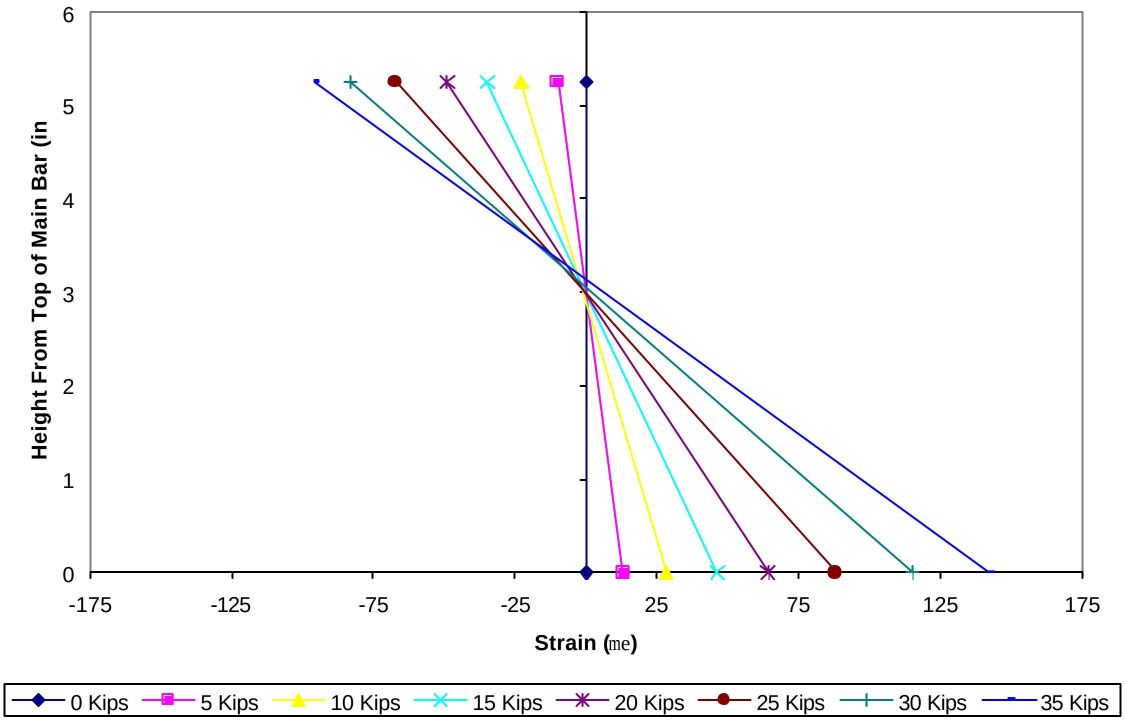

Figure B-216 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-4050K Cycles

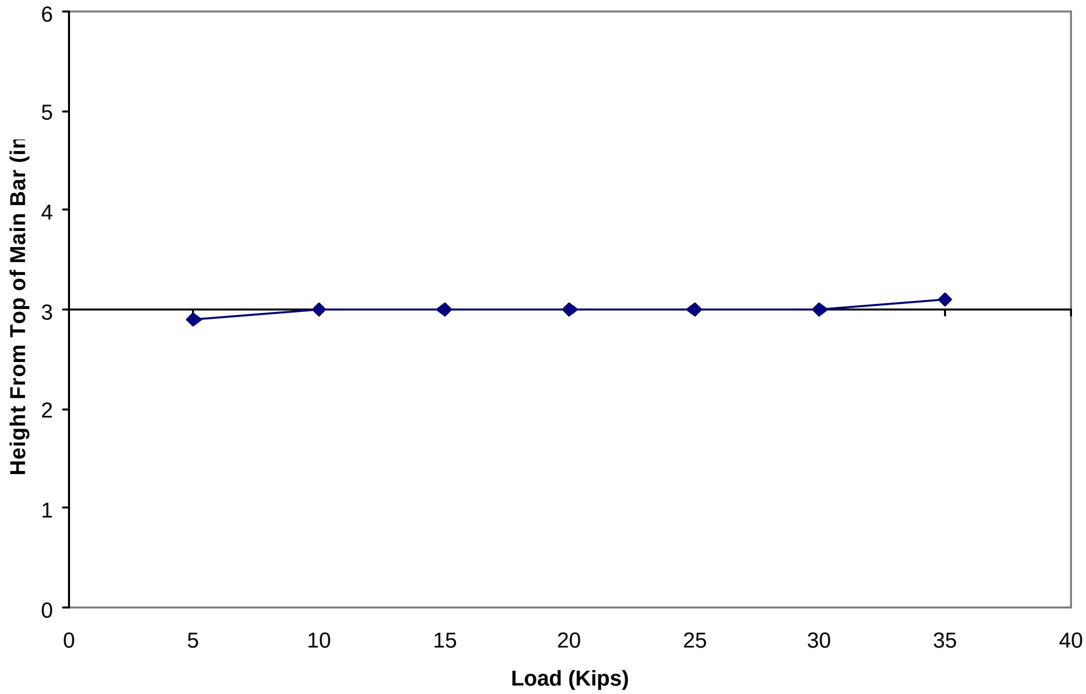

Figure B-217 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-4050K Cycles

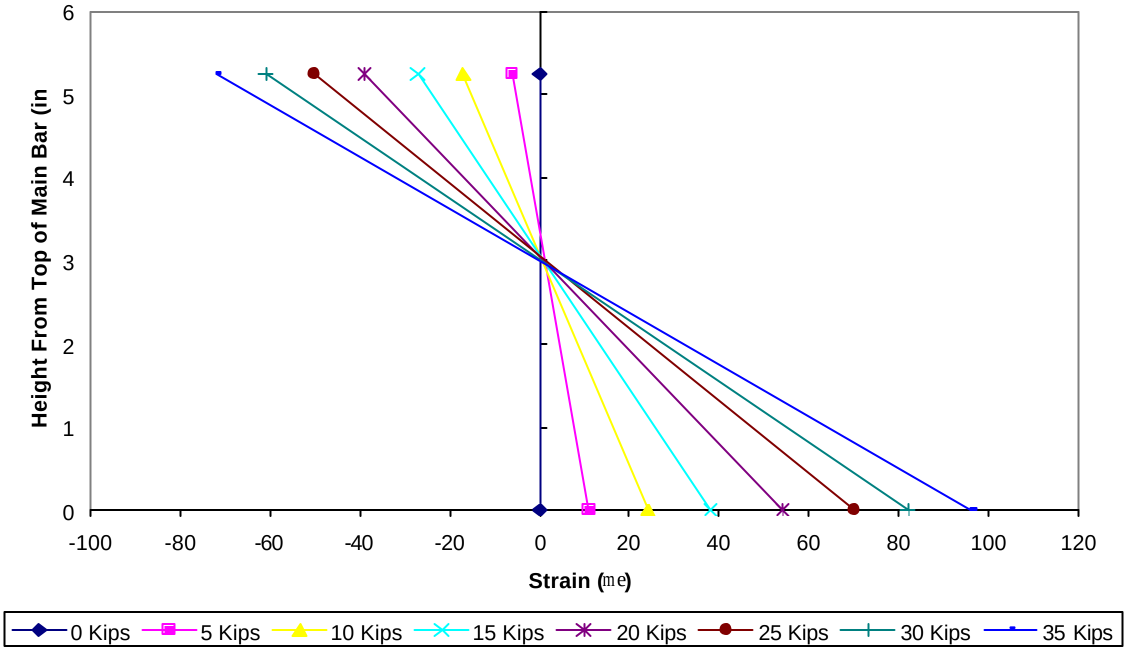

Figure B-218 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-4200K Cycles

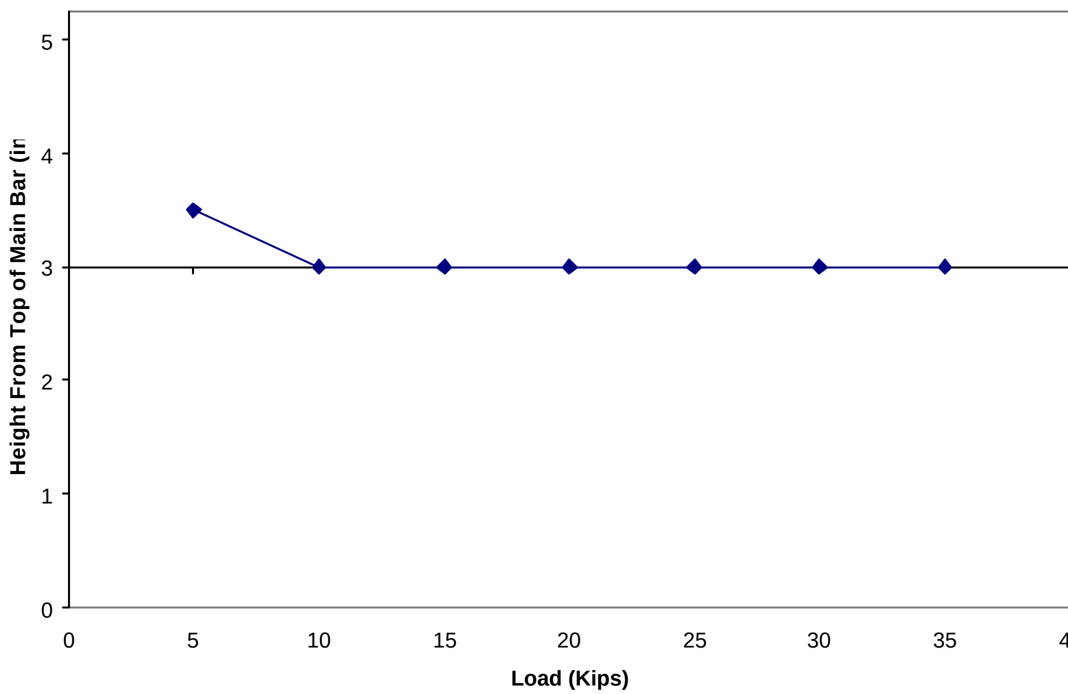

Figure B-219 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-4200K Cycles

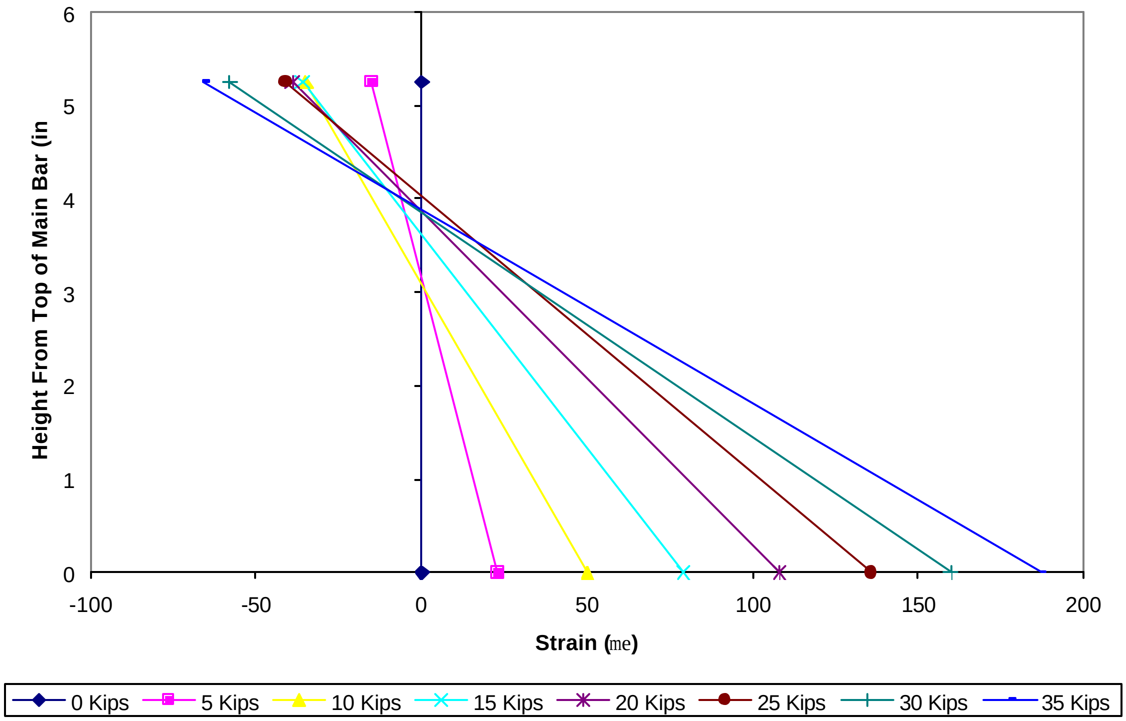

Figure B-220 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-4200K Cycles

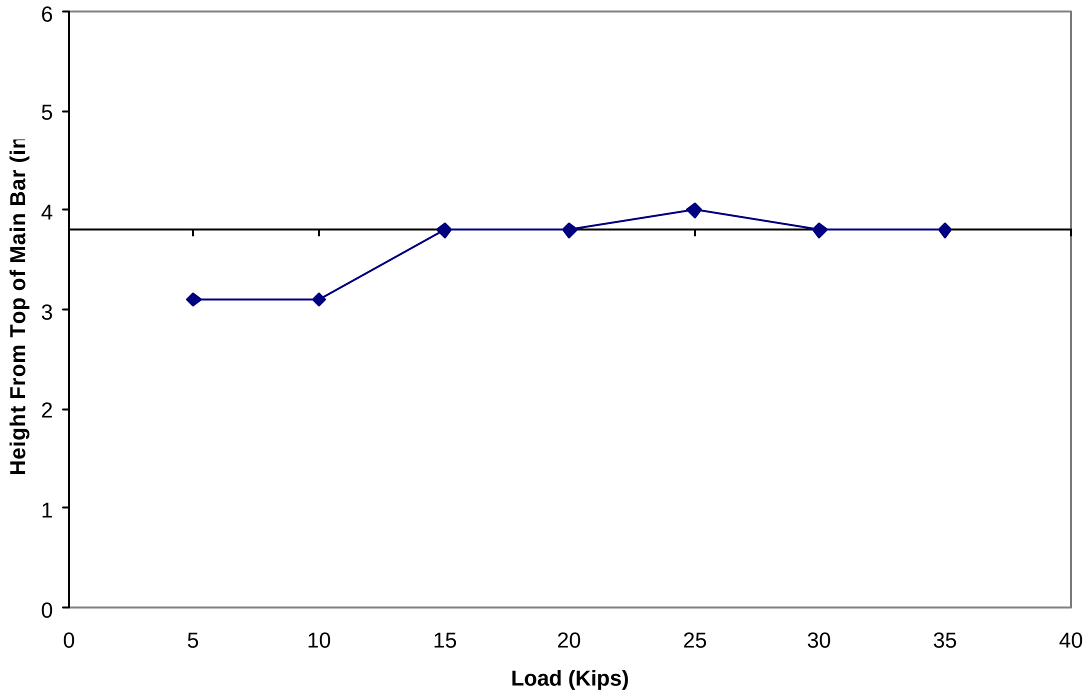

Figure B-221 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-4200K Cycles

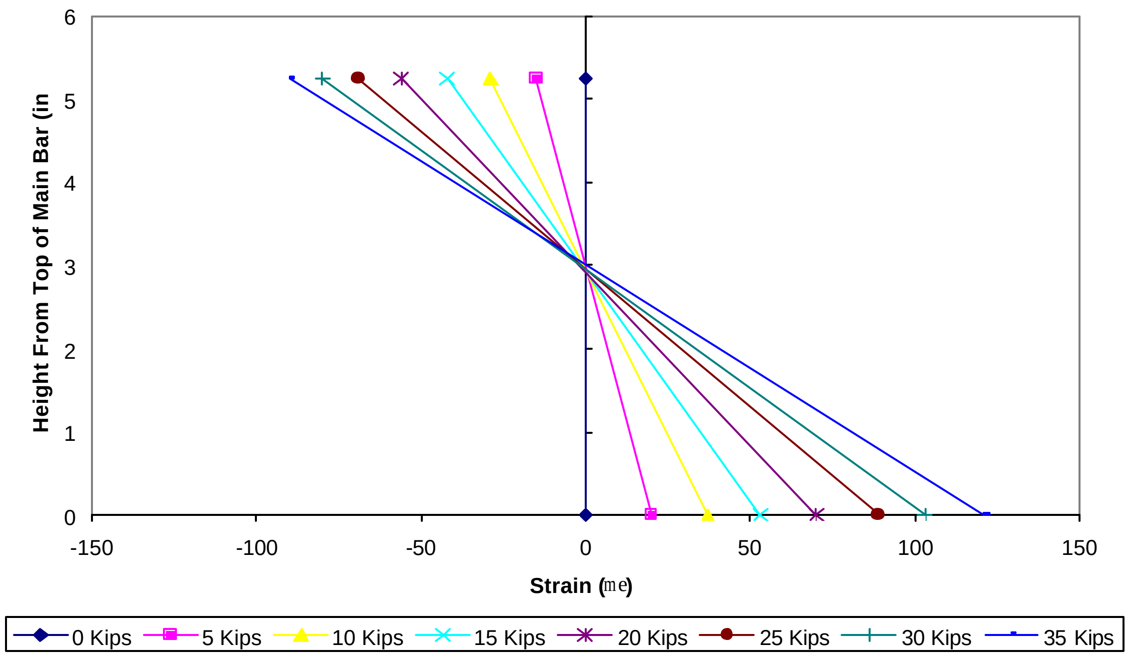

Figure B-222 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-4350K Cycles

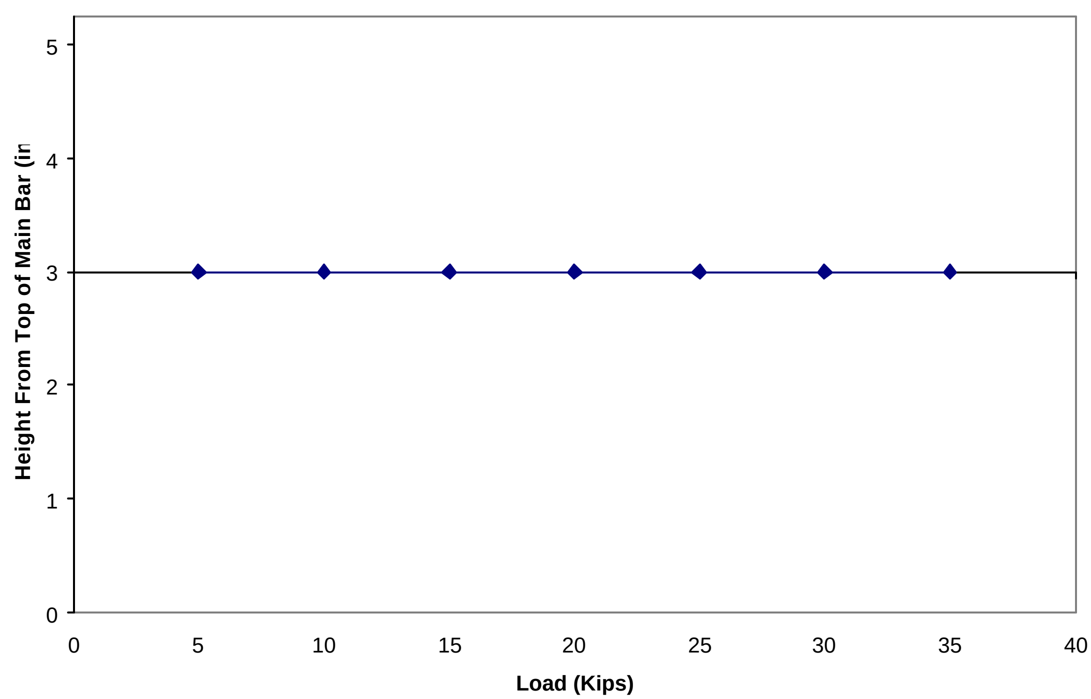

Figure B-223 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-4350K Cycles

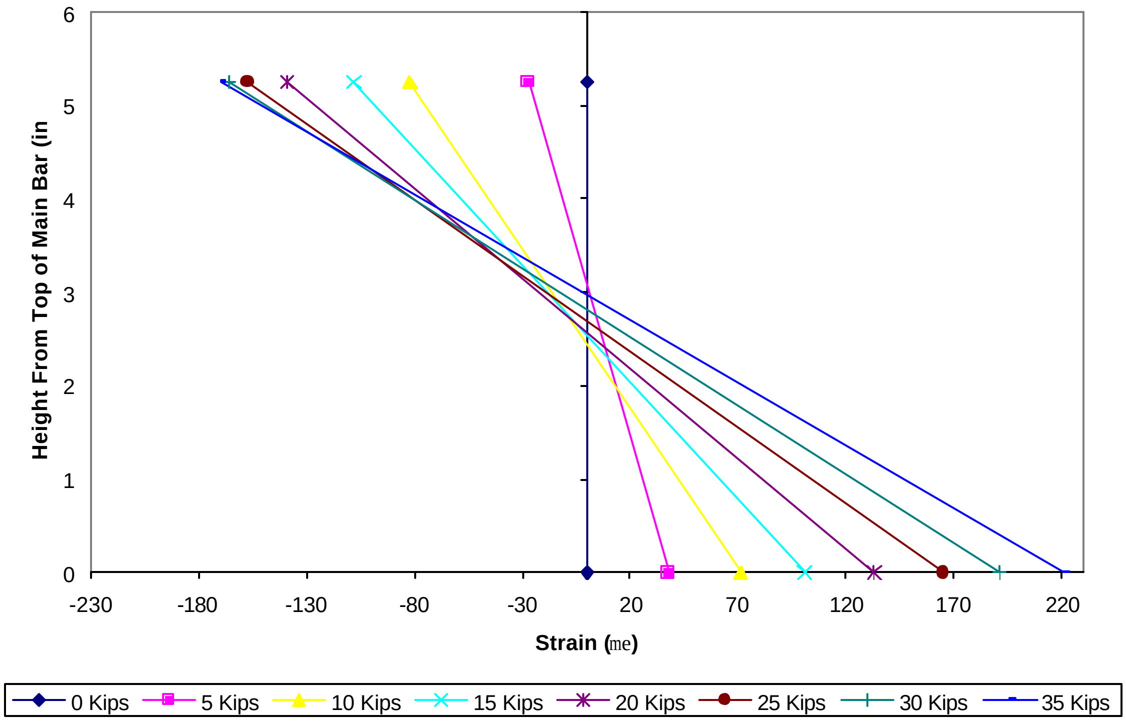

Figure B-224 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-4350K Cycles

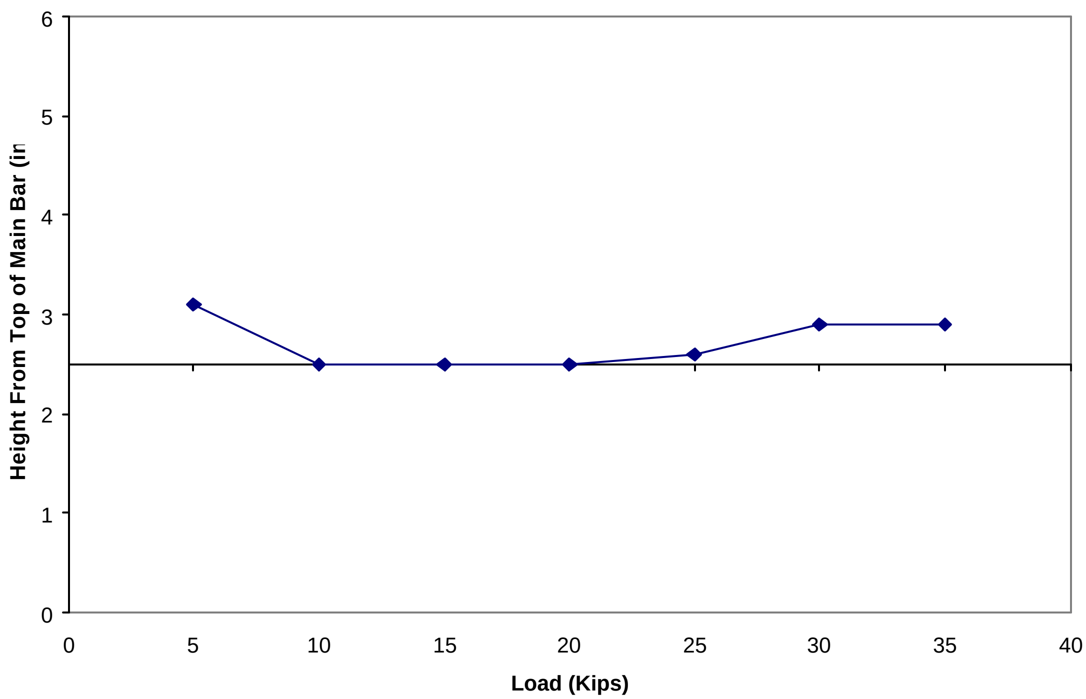

Figure B-225 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-4350K Cycles

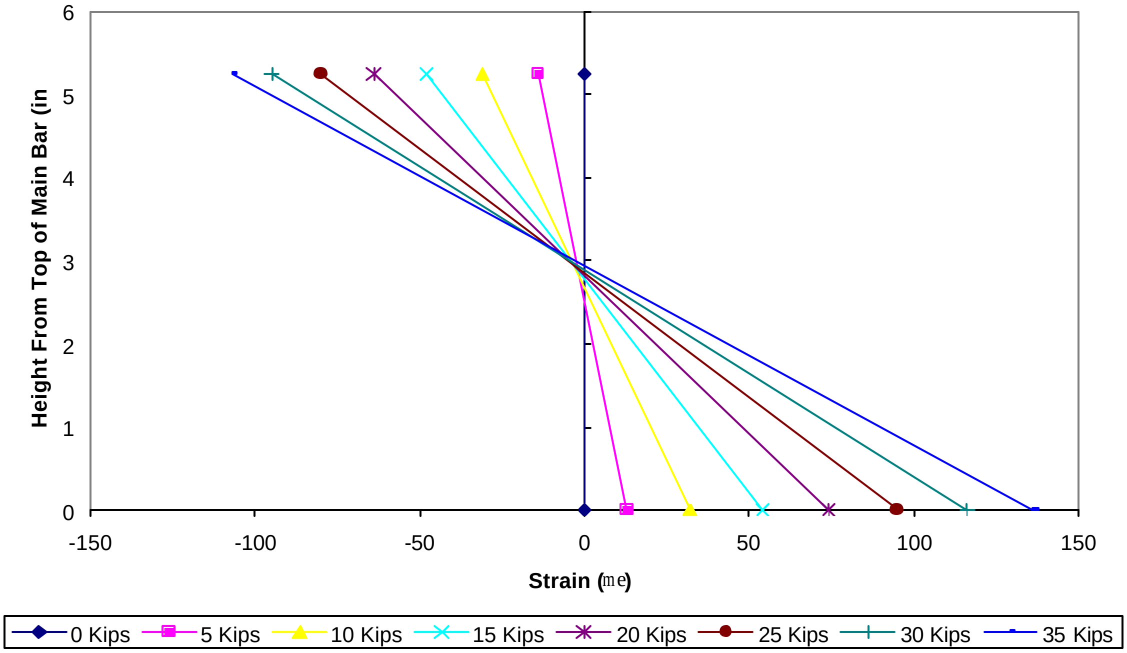

Figure B-226 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-4400K Cycles

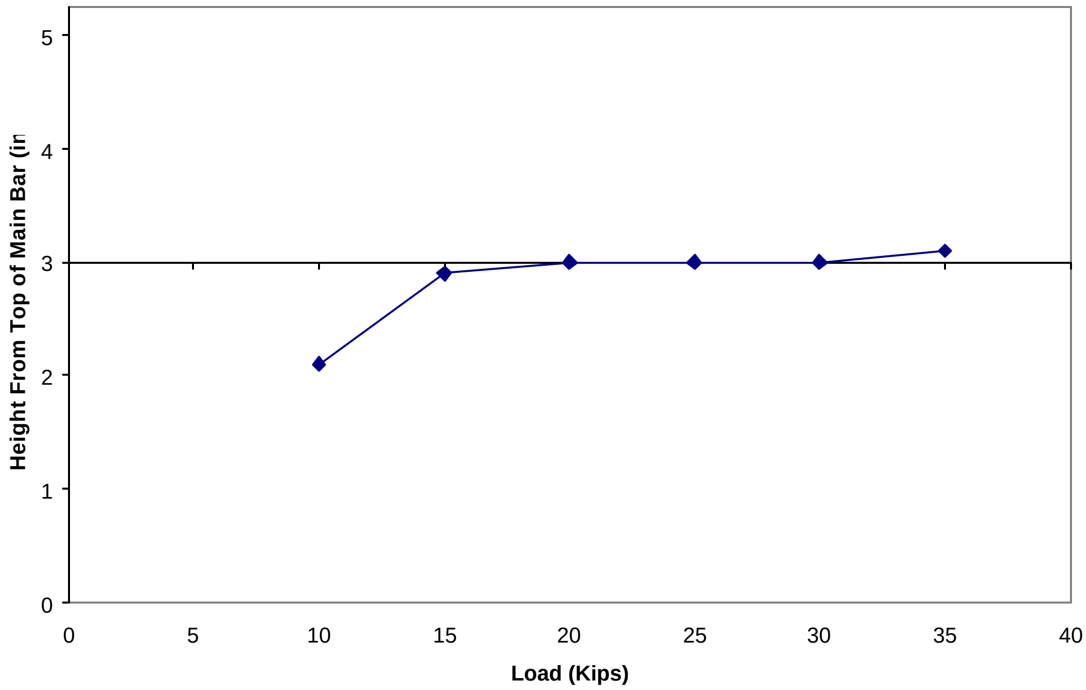

Figure B-227 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-4400K Cycles

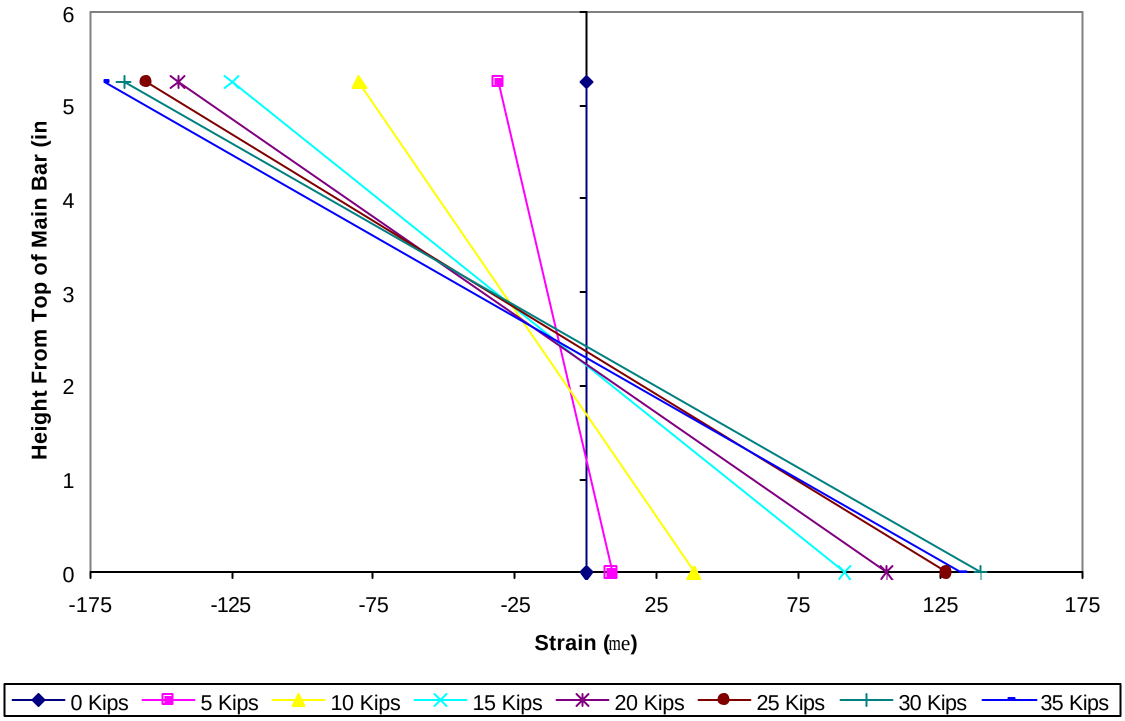

Figure B-228 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-4400K Cycles

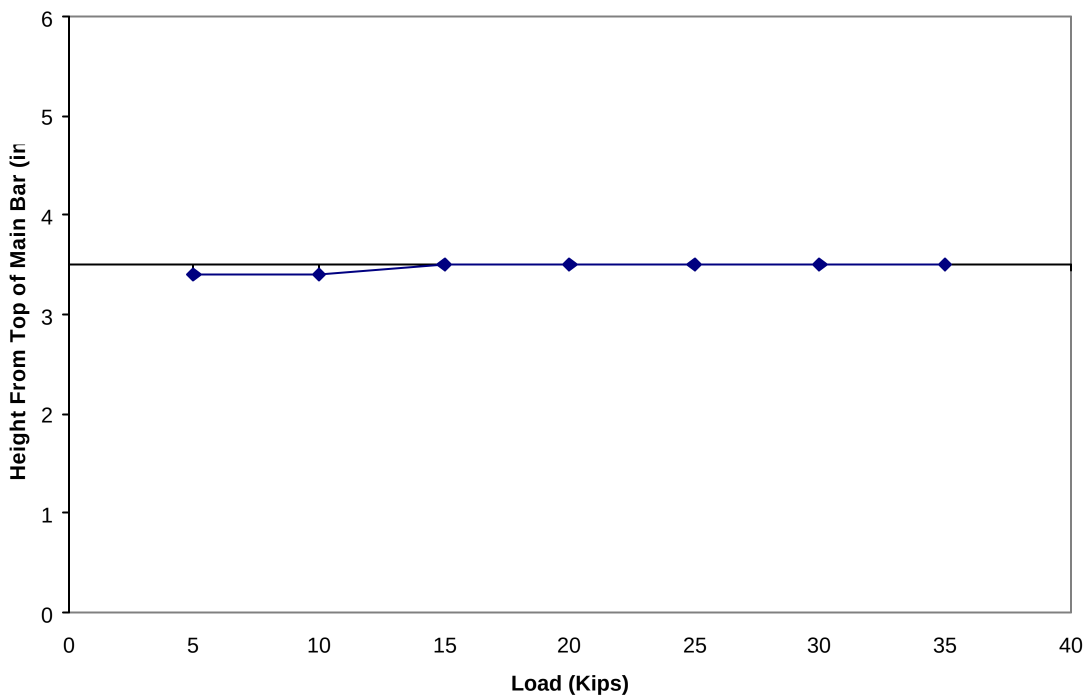

Figure B-229 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-4400K Cycles

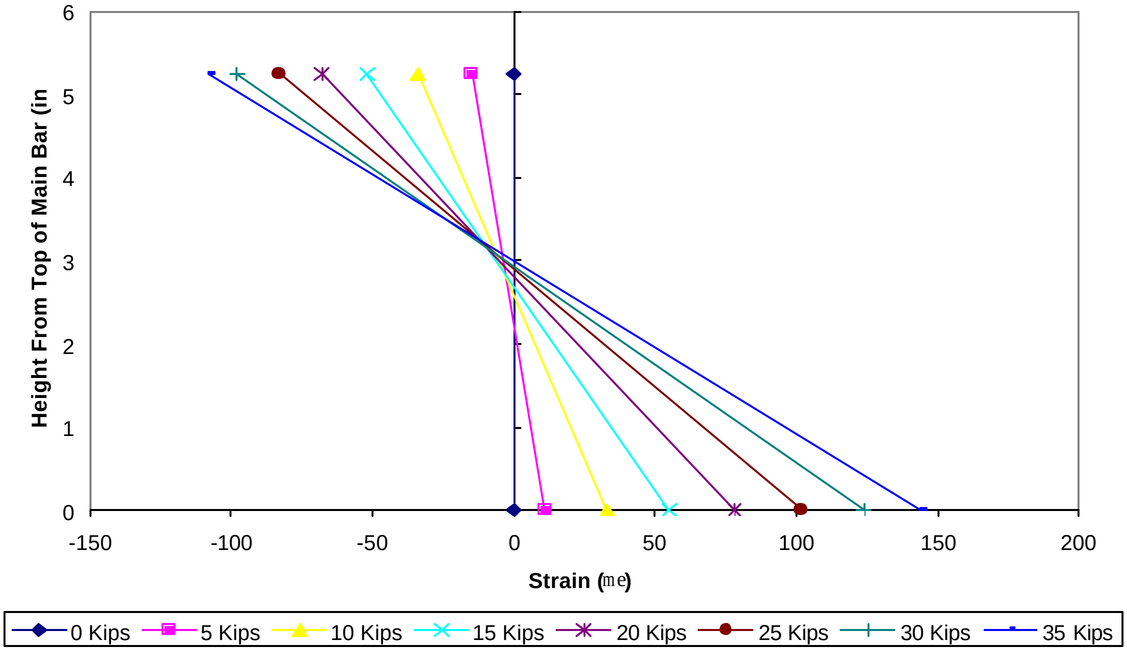

Figure B-230 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-4550K Cycles

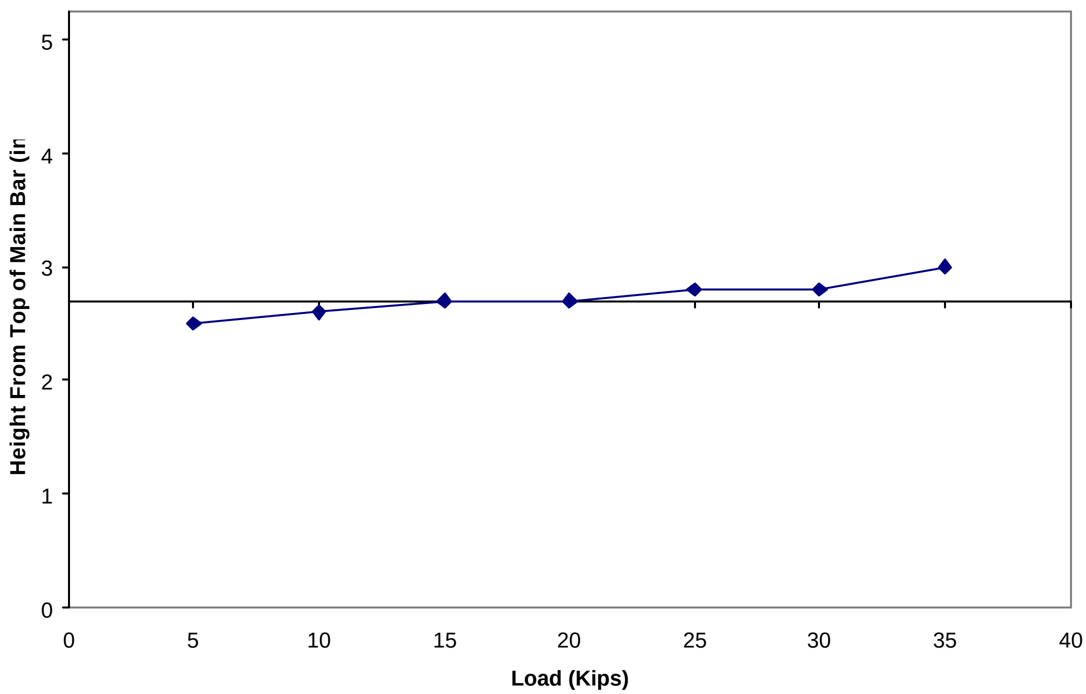

Figure B-231 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-4550K Cycles

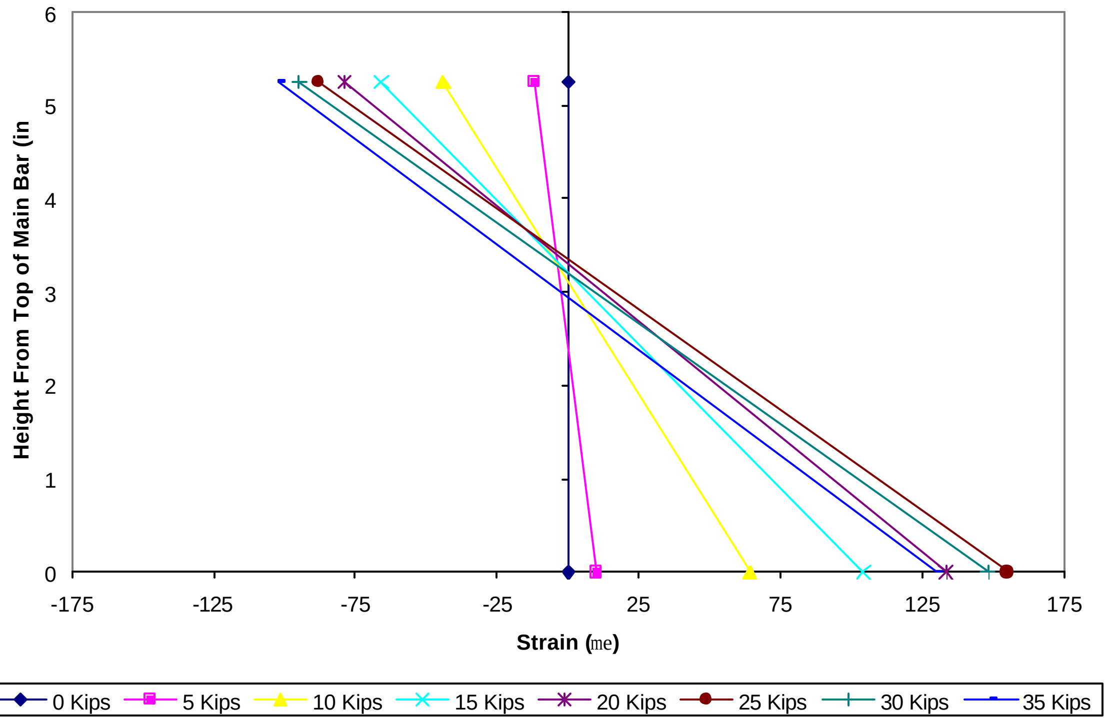

Figure B-232 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-4550K Cycles

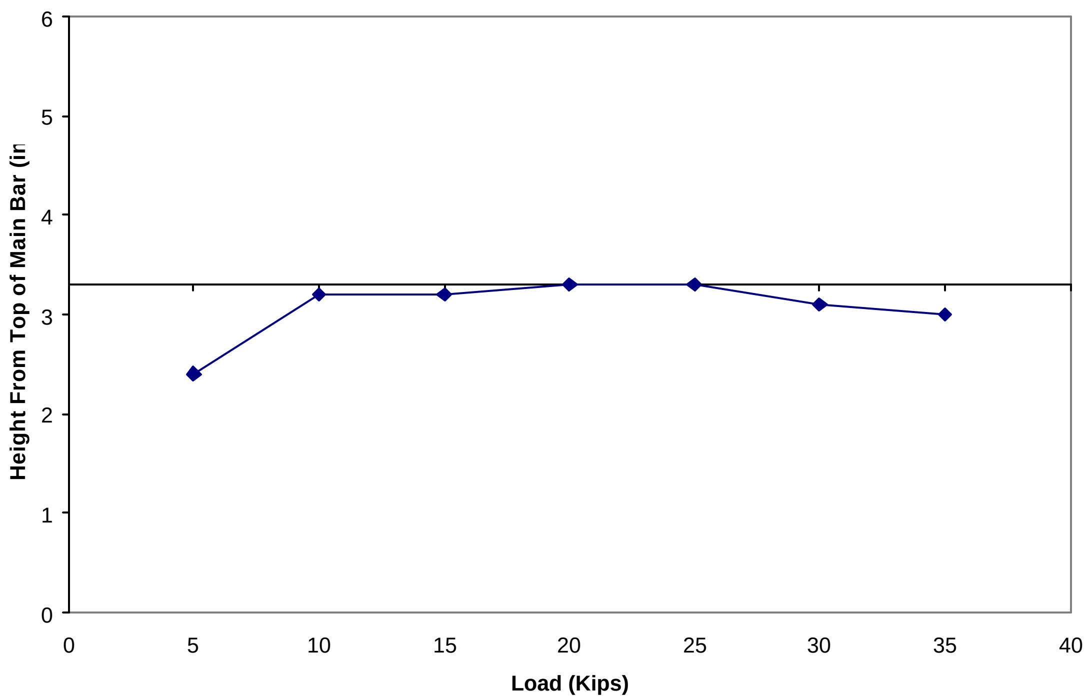

Figure B-233 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-4550K Cycles

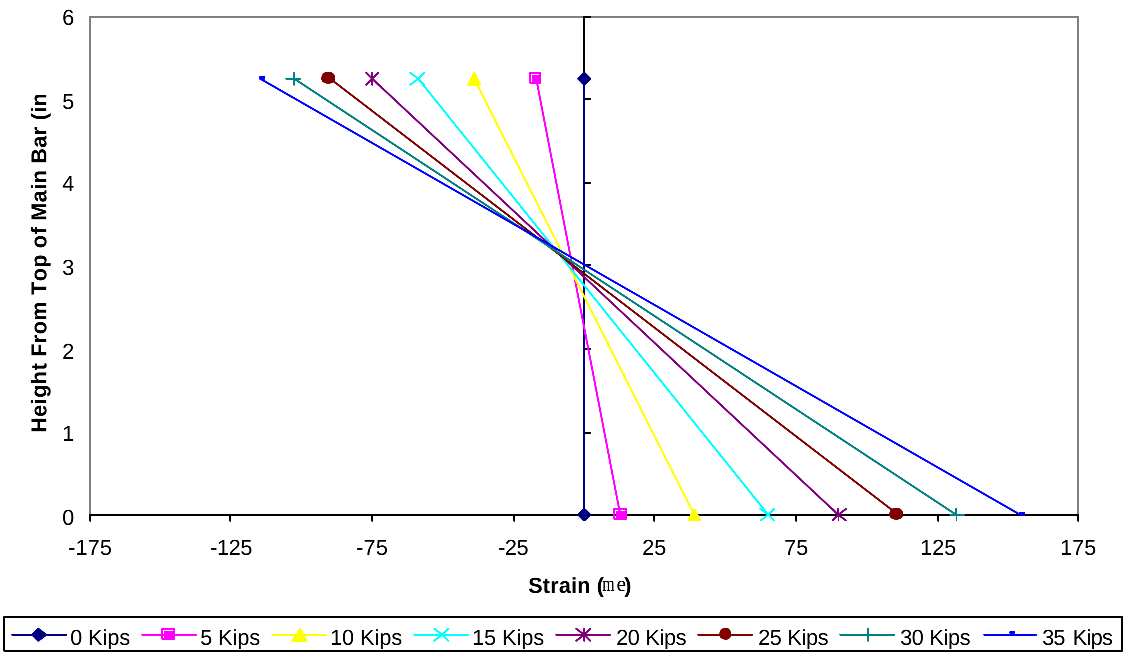

Figure B-234 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-4700K Cycles

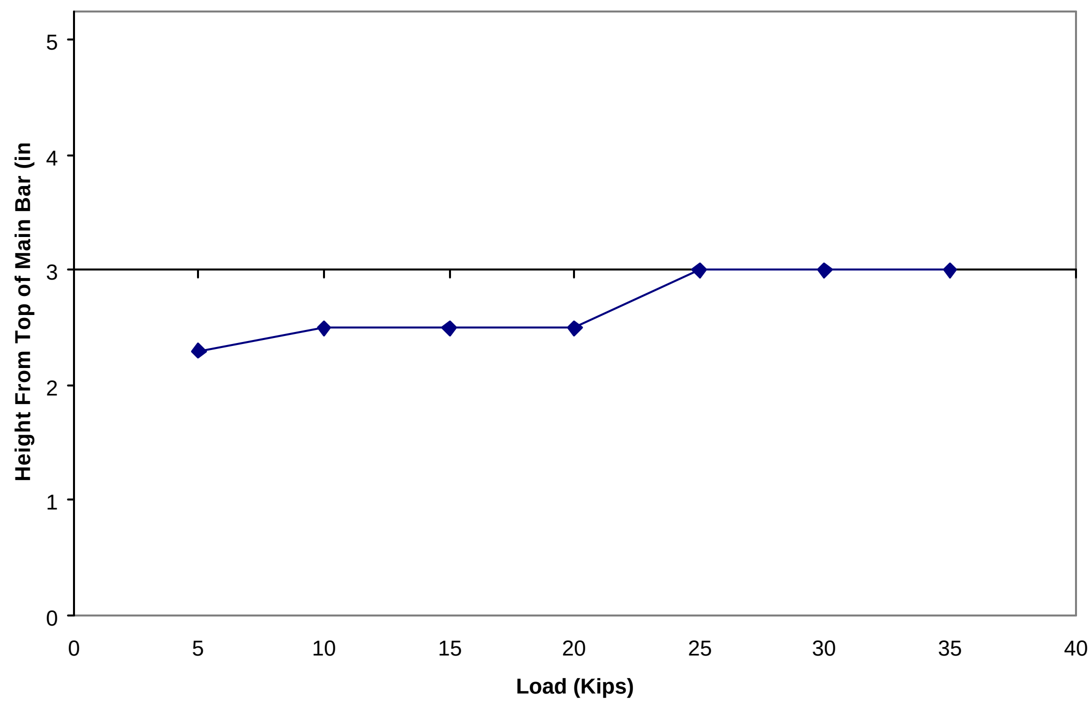

Figure B-235 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-4700K Cycles

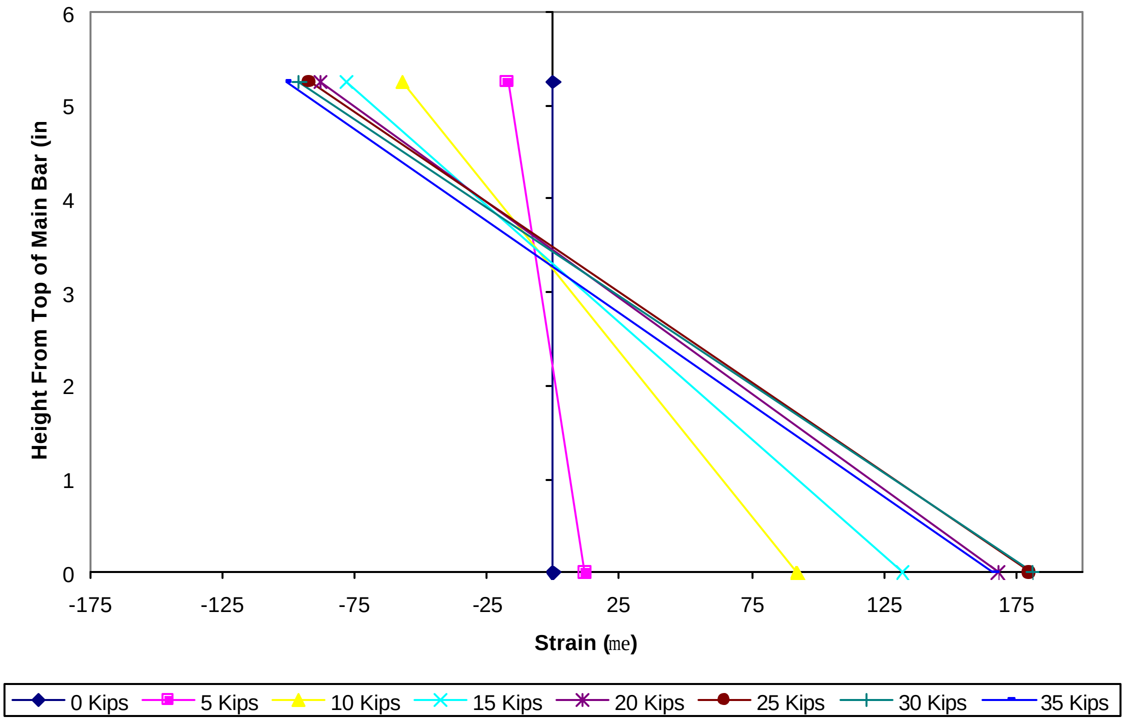

Figure B-236 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-4700K Cycles

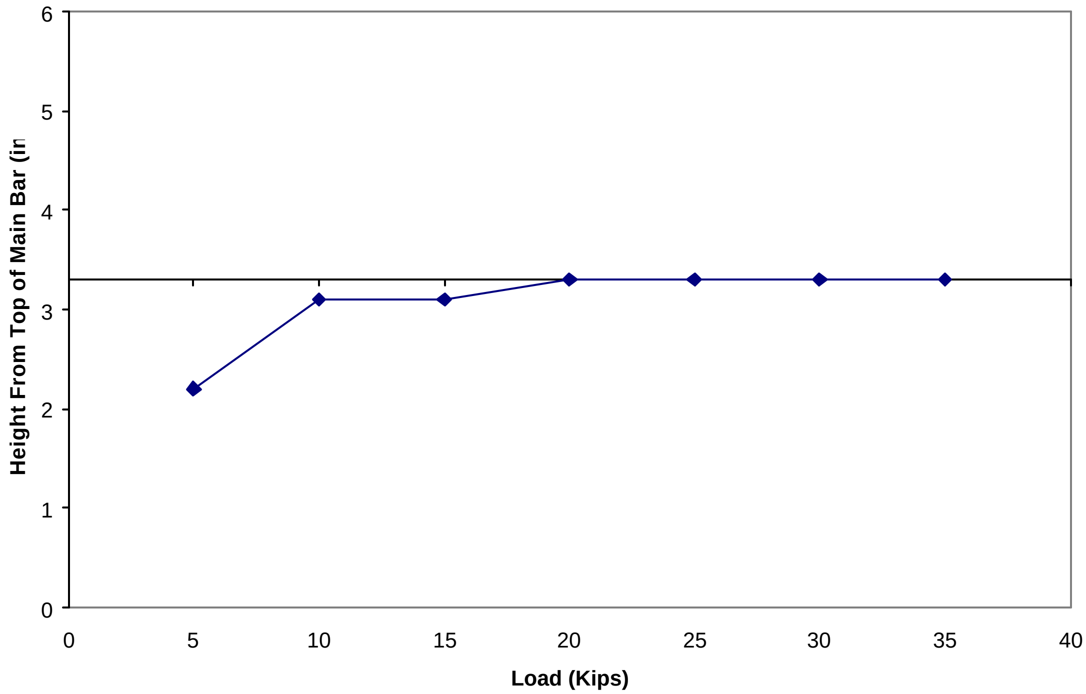

Figure B-237 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-4700K Cycles

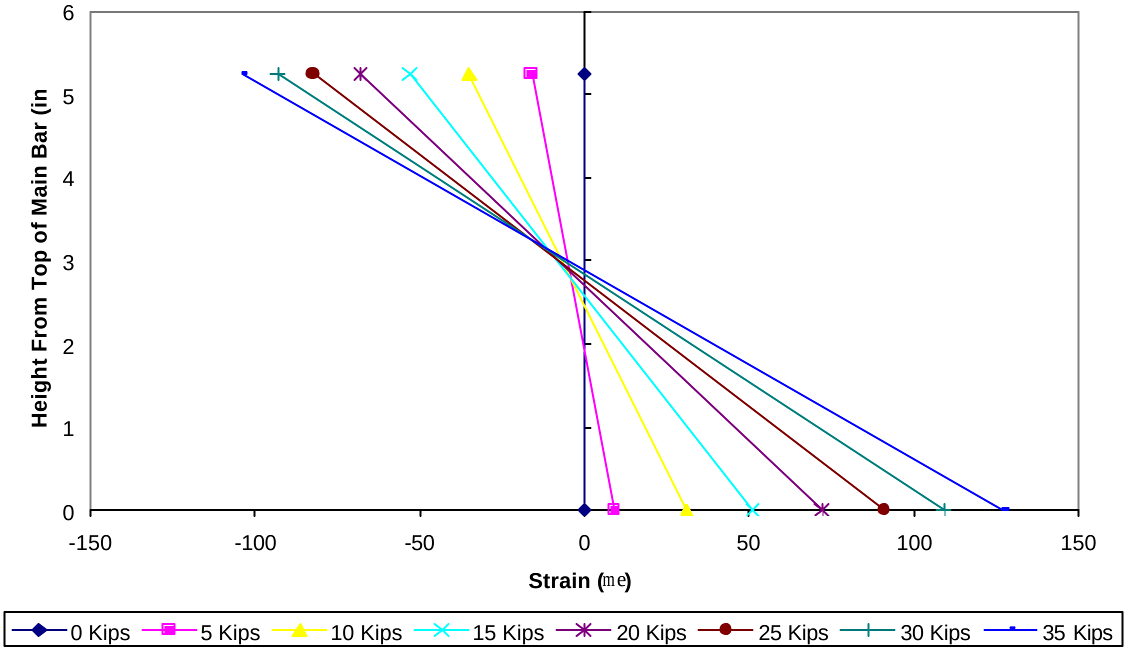

Figure B-238 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-4850K Cycles

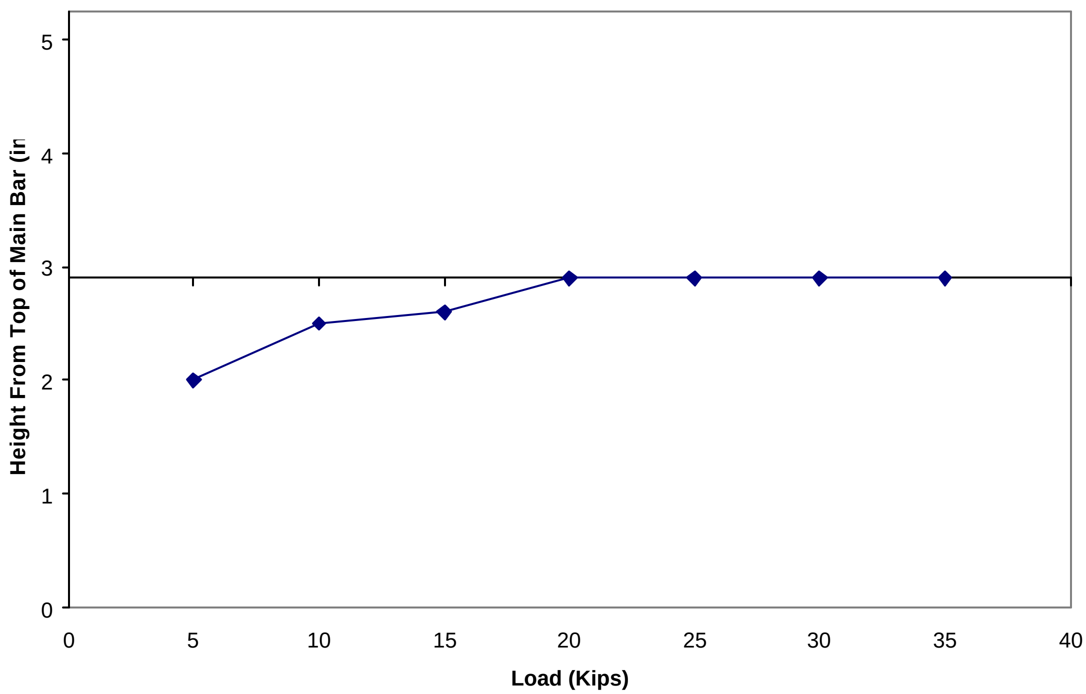

Figure B-239 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-4850K Cycles

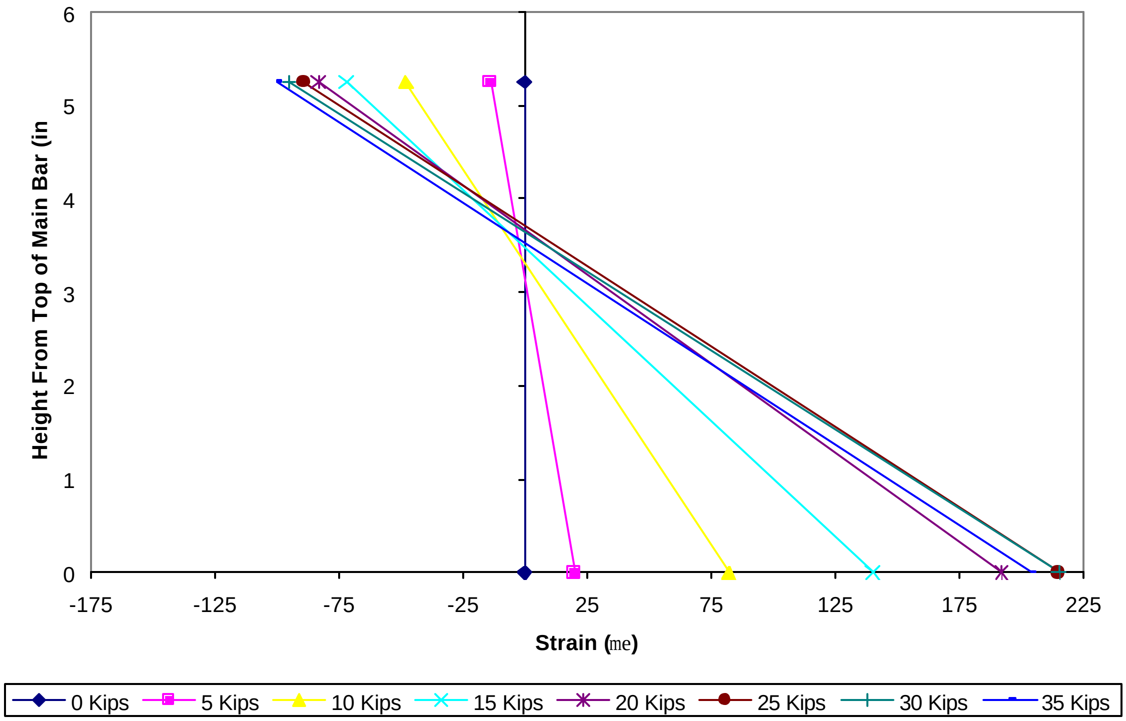

Figure B-240 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-4850K Cycles

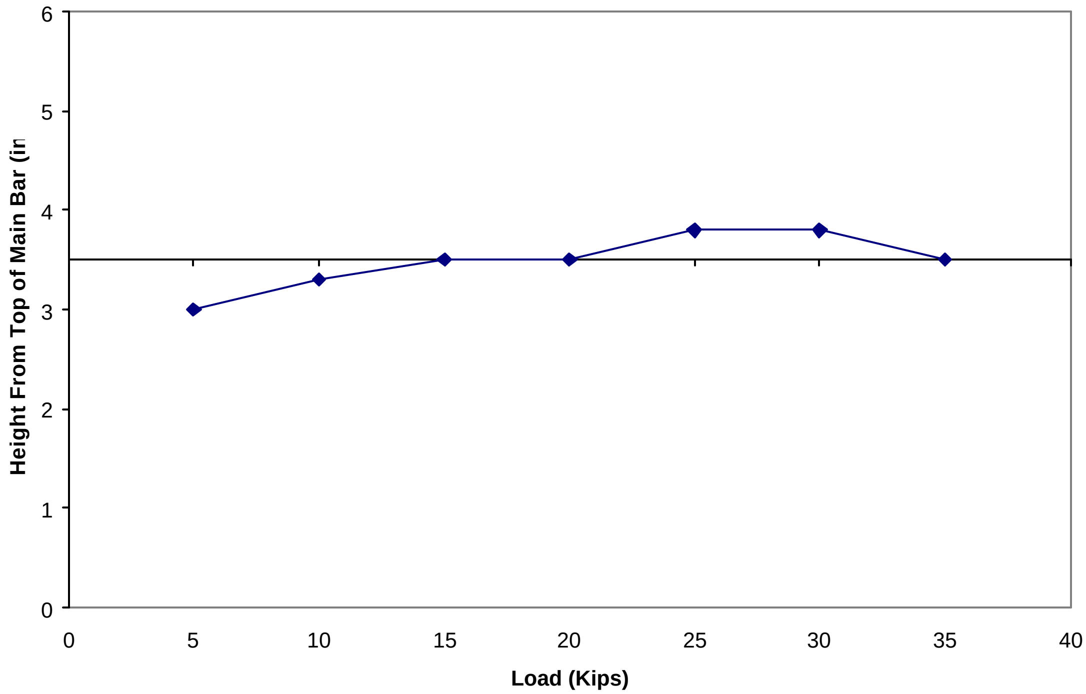

Figure B-241 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-4850K Cycles

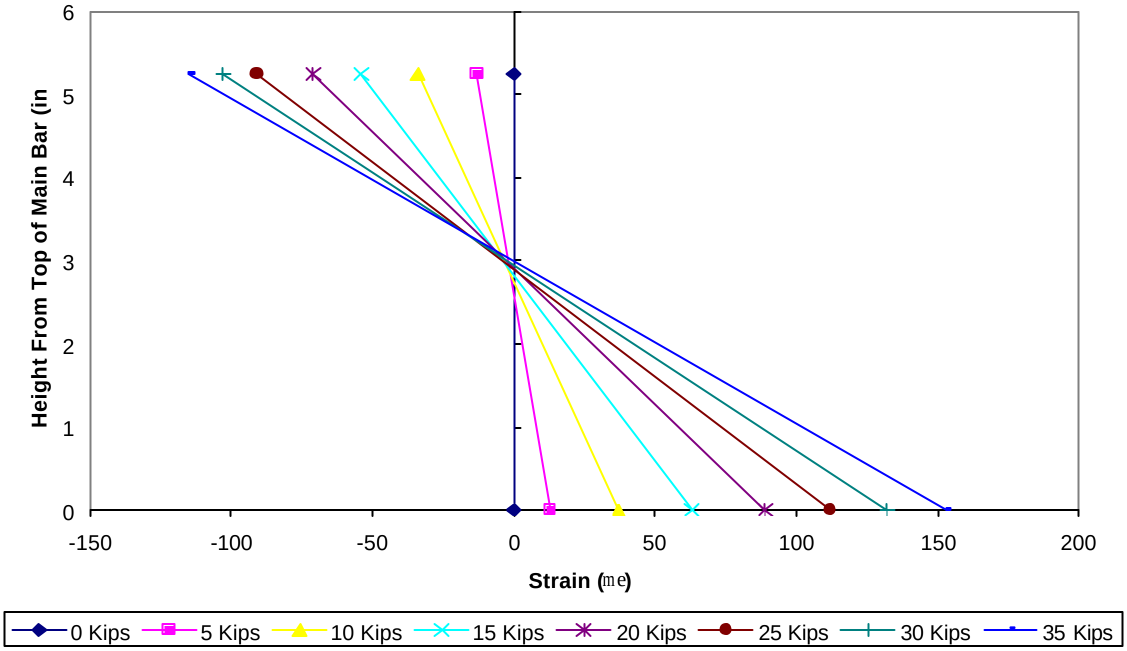

Figure B-242 Fatigue Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution-5000K Cycles

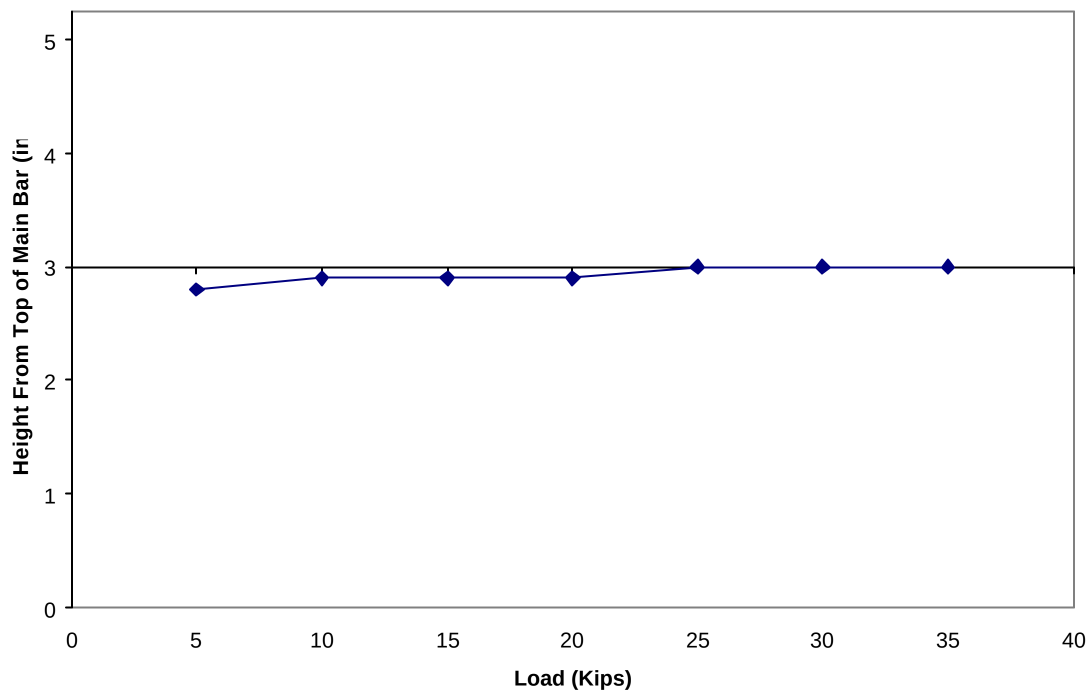

Figure B-243 Fatigue Specimen #1 Main Bar #1
- Neutral Axis Location-5000K Cycles

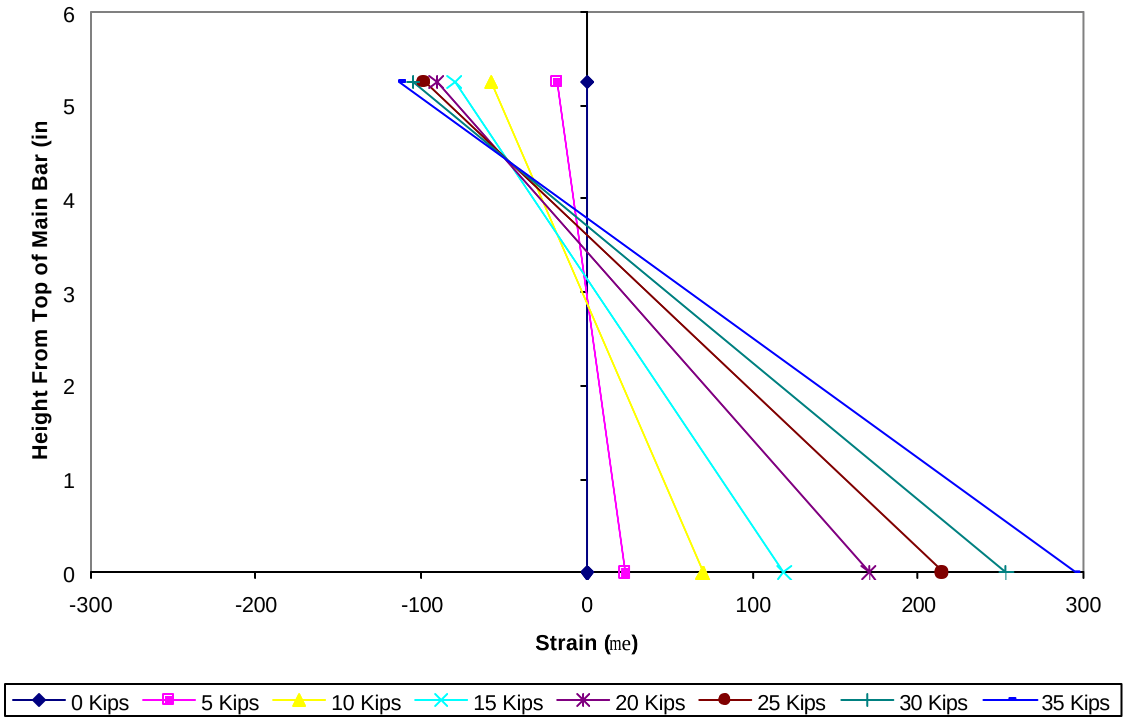

Figure B-244 Fatigue Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution-5000K Cycles

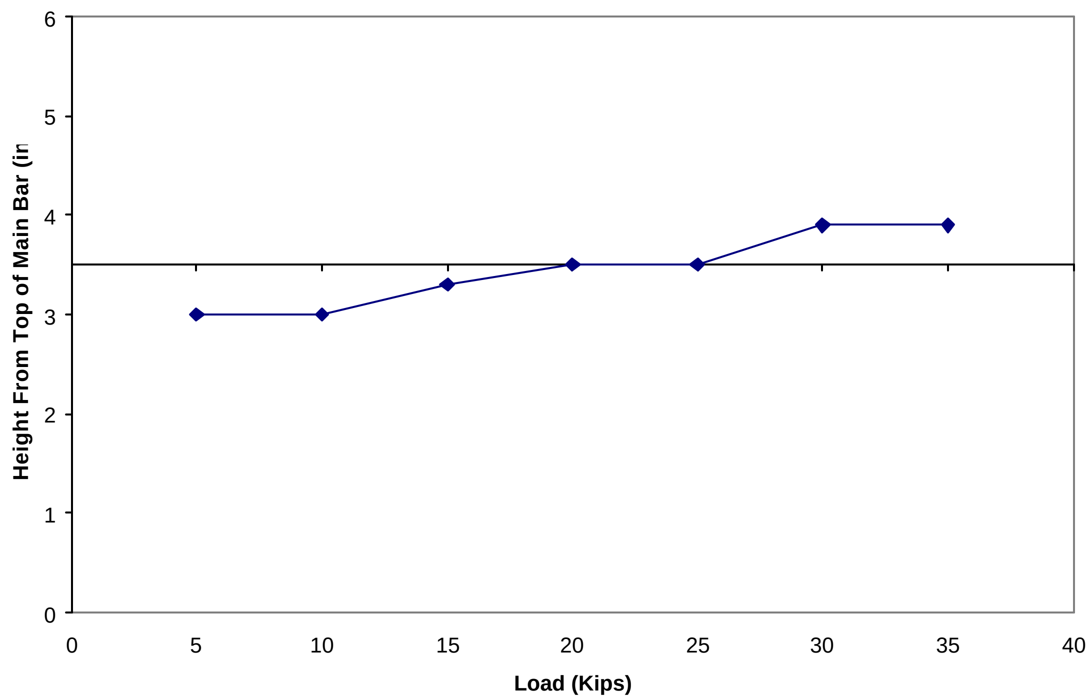

Figure B-245 Fatigue Specimen #1 Main Bar #2
- Neutral Axis Location-5000K Cycles

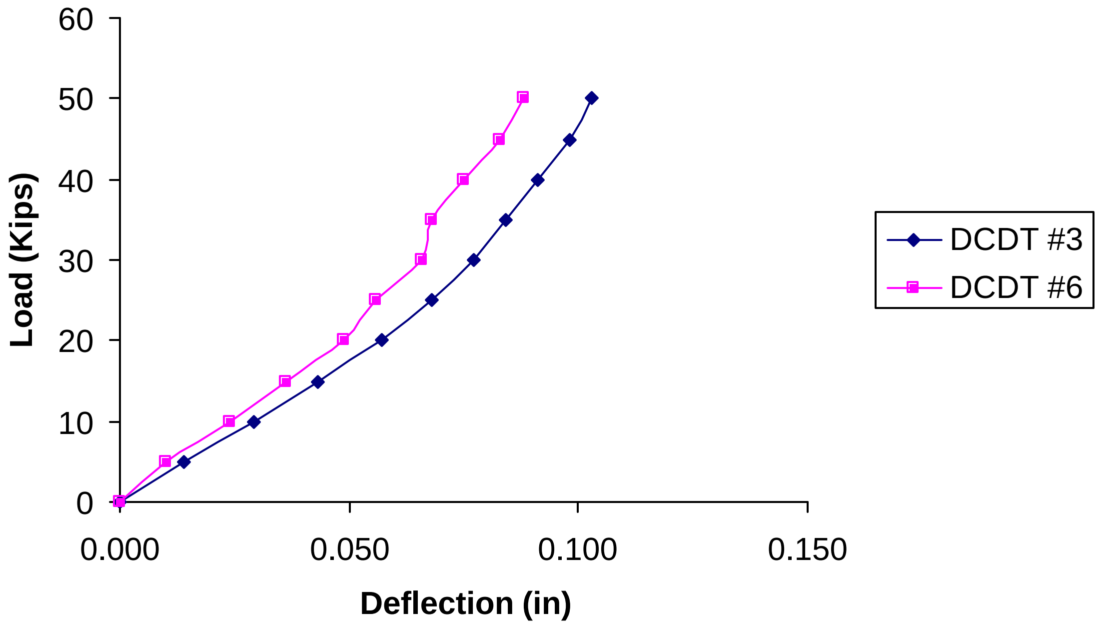

Figure B-246 Fatigue Specimen #2 Main Bar #1-Benchmark

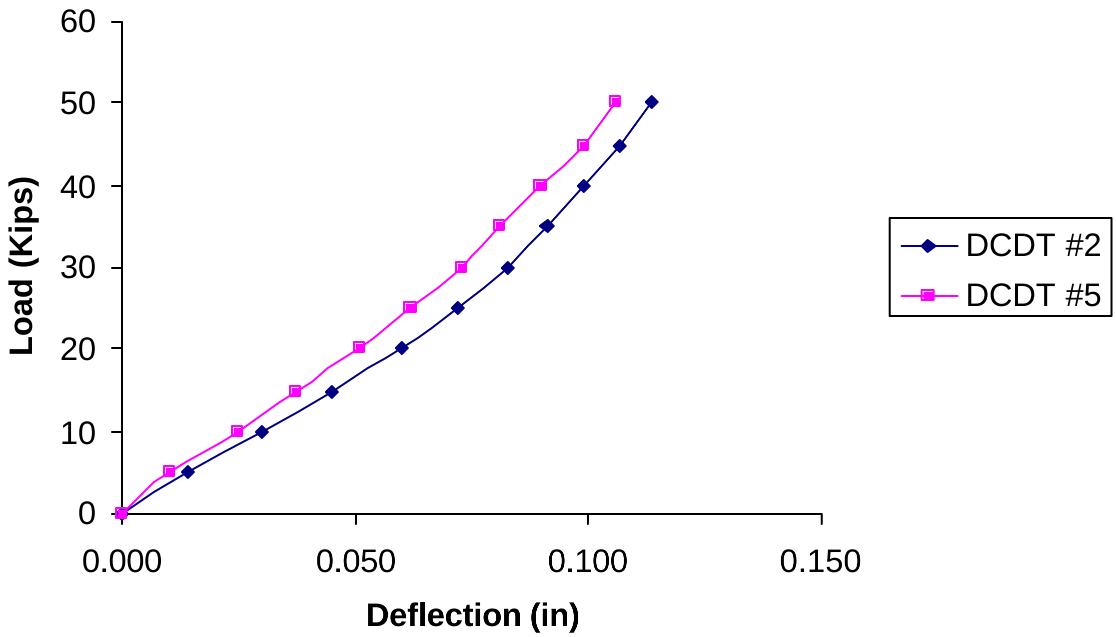

Figure B-247 Fatigue Specimen #2 Main Bar #2-Benchmark

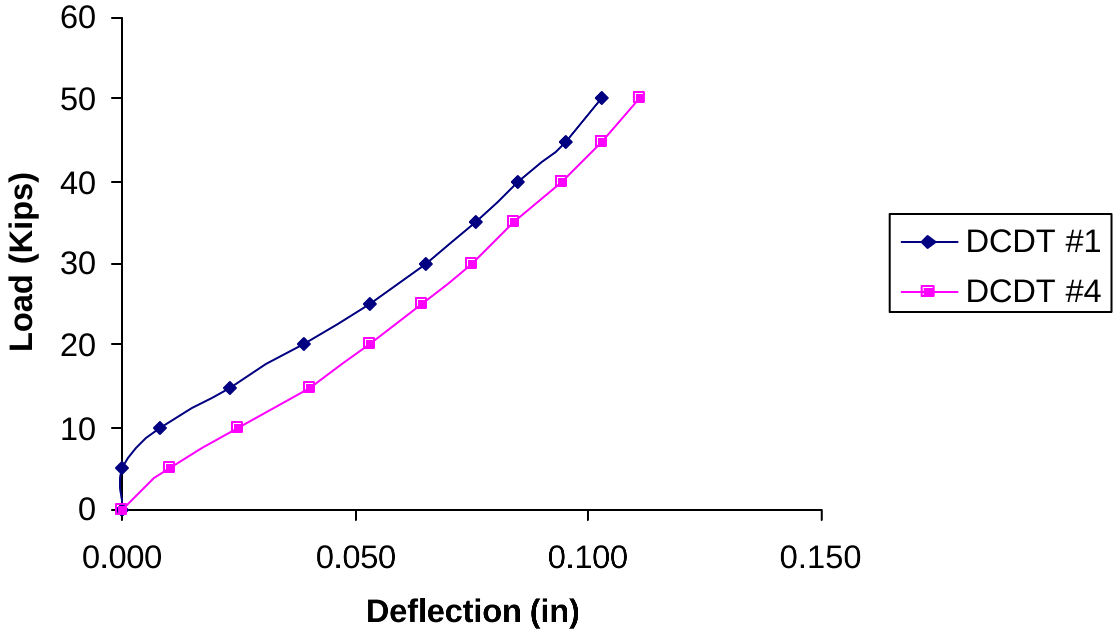

Figure B-248 Fatigue Specimen #2 Main Bar #3-Benchmark

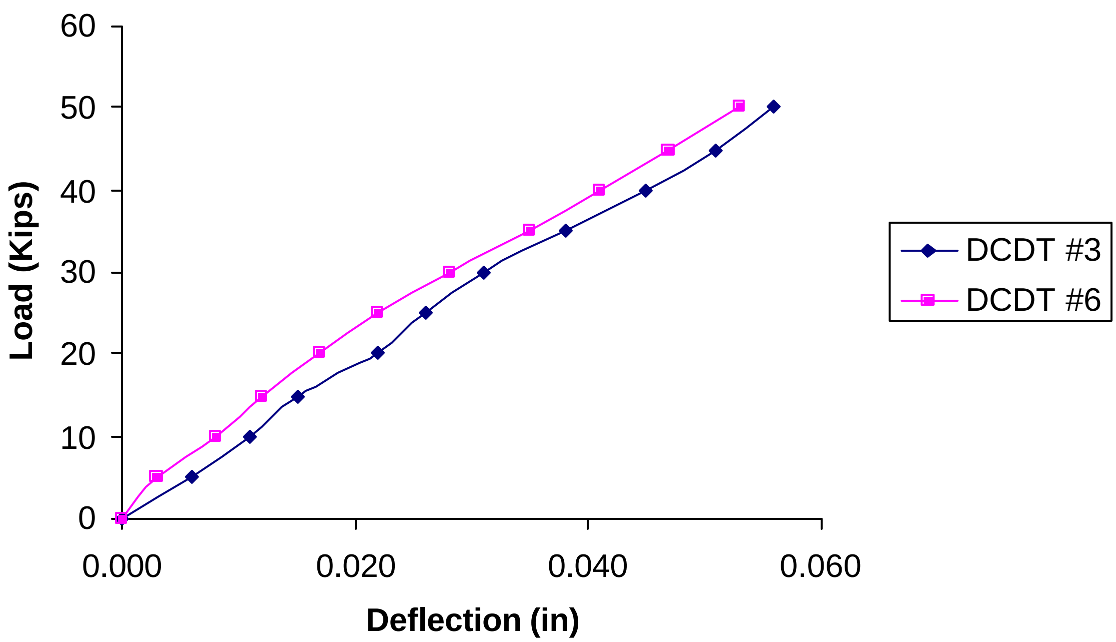

Figure B-249 Fatigue Specimen #2 Main Bar #1-150K Cycles

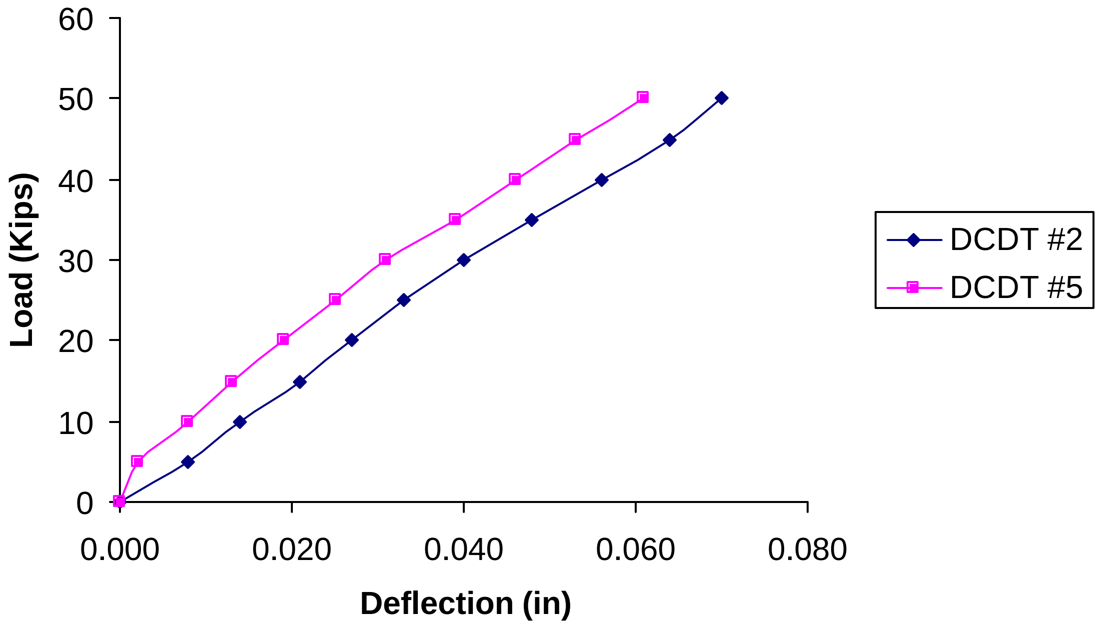

Figure B-250 Fatigue Specimen #2 Main Bar #2-150K Cycles

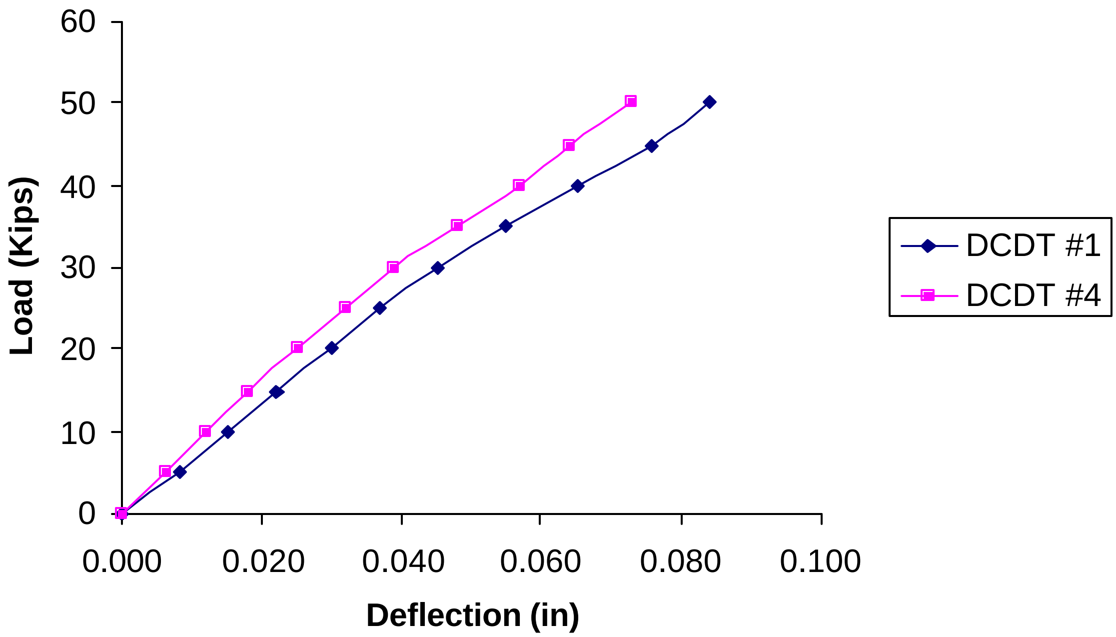

Figure B-251 Fatigue Specimen #2 Main Bar #3-150K Cycles

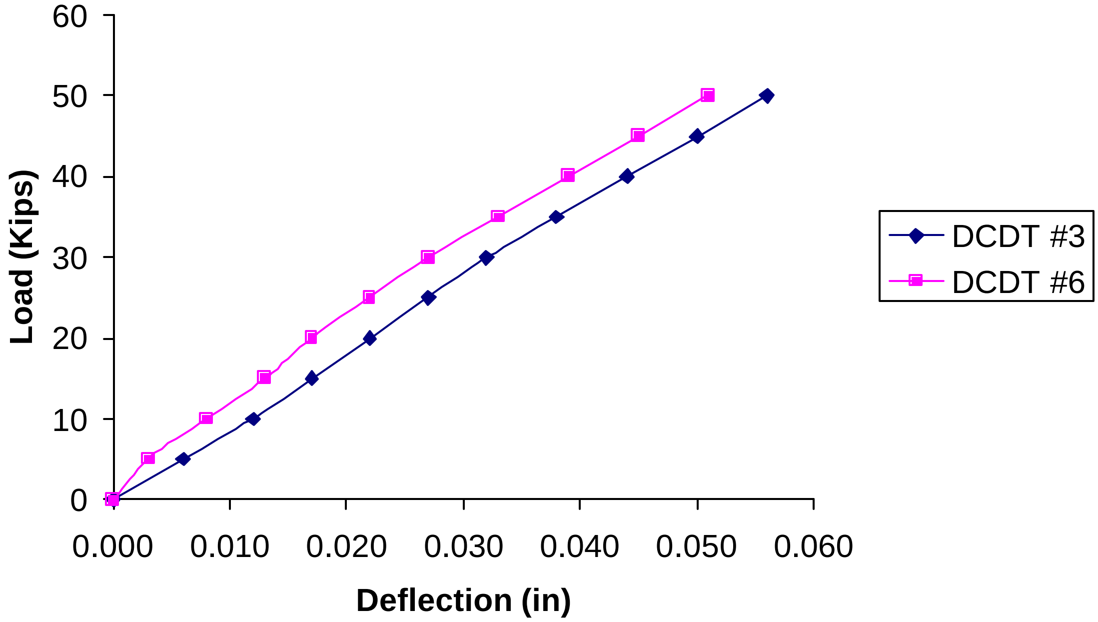

Figure B-252 Fatigue Specimen #2 Main Bar #1-300K Cycles

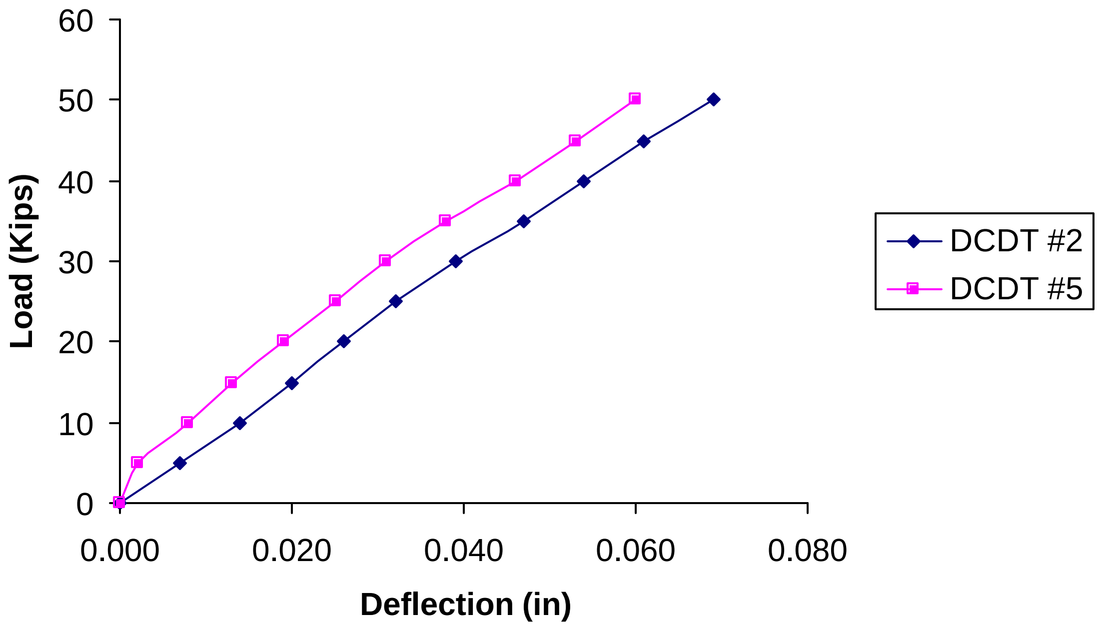

Figure B-253 Fatigue Specimen #2 Main Bar #2-300K Cycles

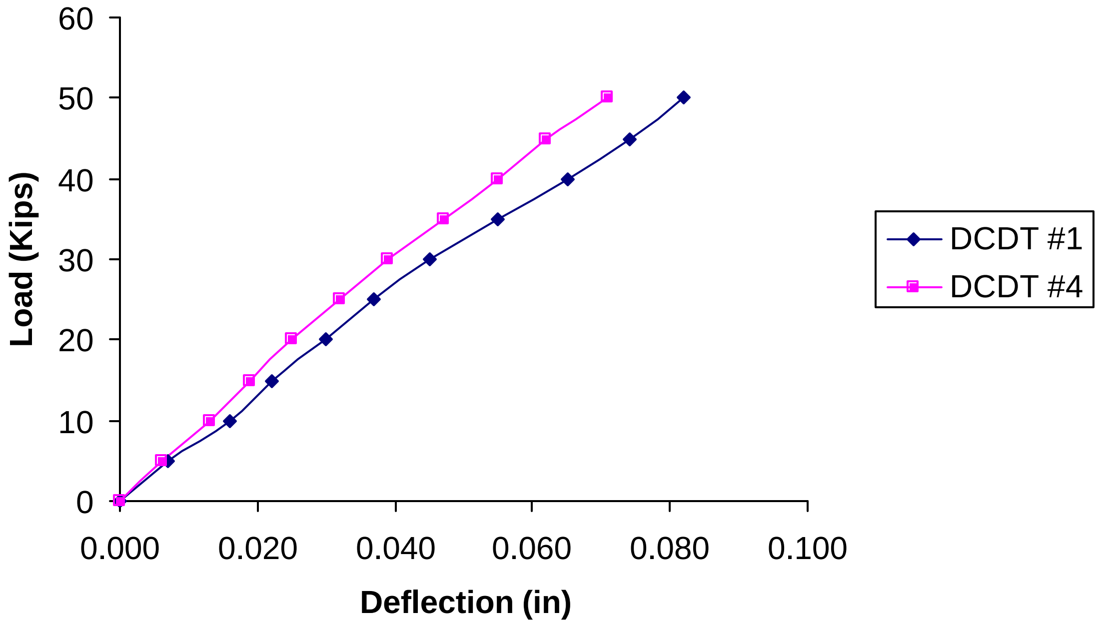

Figure B-254 Fatigue Specimen #2 Main Bar #3-300K Cycles

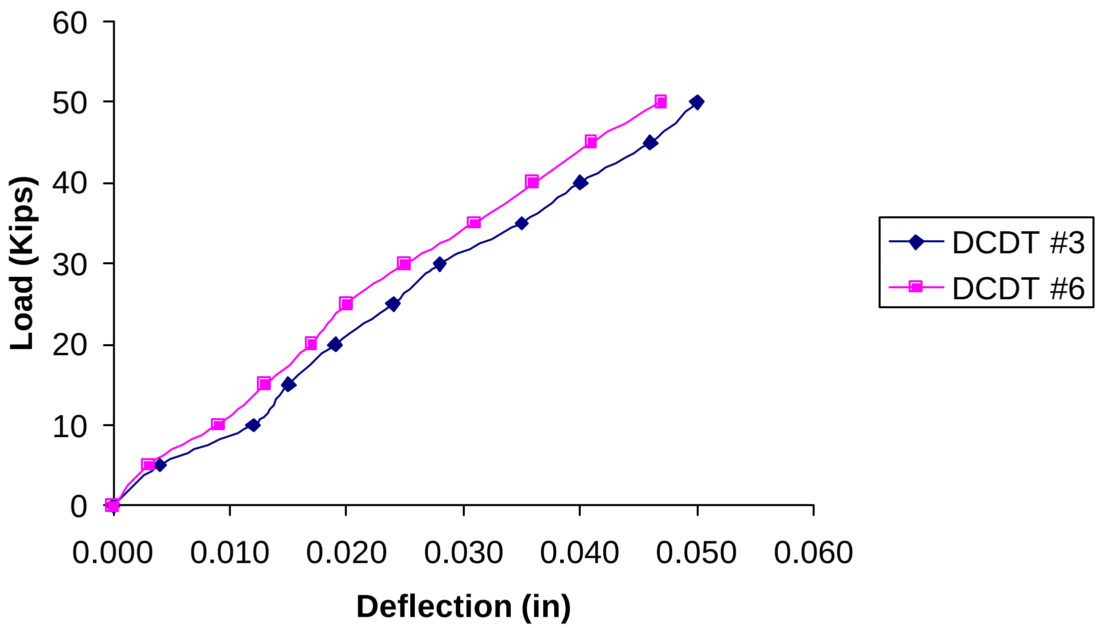

Figure B-255 Fatigue Specimen #2 Main Bar #1-450K Cycles

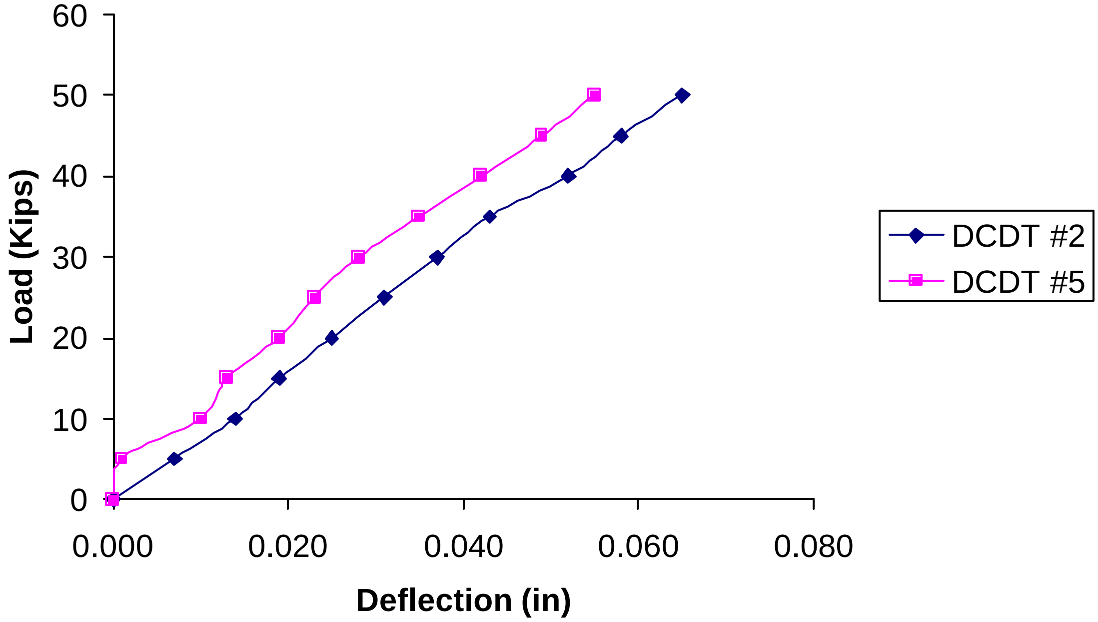

Figure B-256 Fatigue Specimen #2 Main Bar #2-450K Cycles

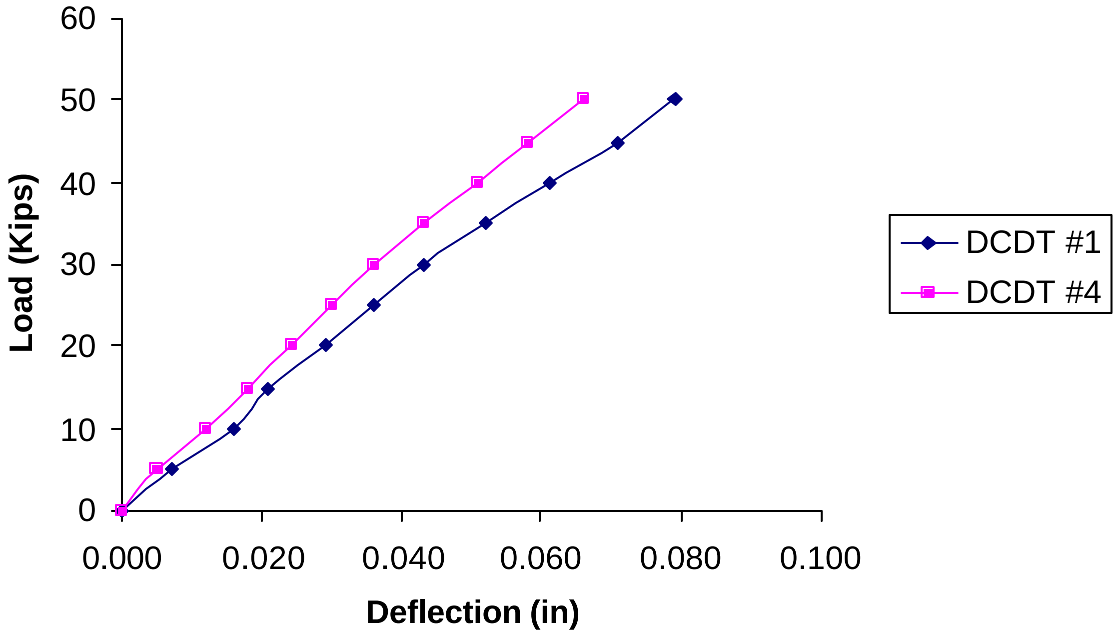

Figure B-257 Fatigue Specimen #2 Main Bar #3-450K Cycles

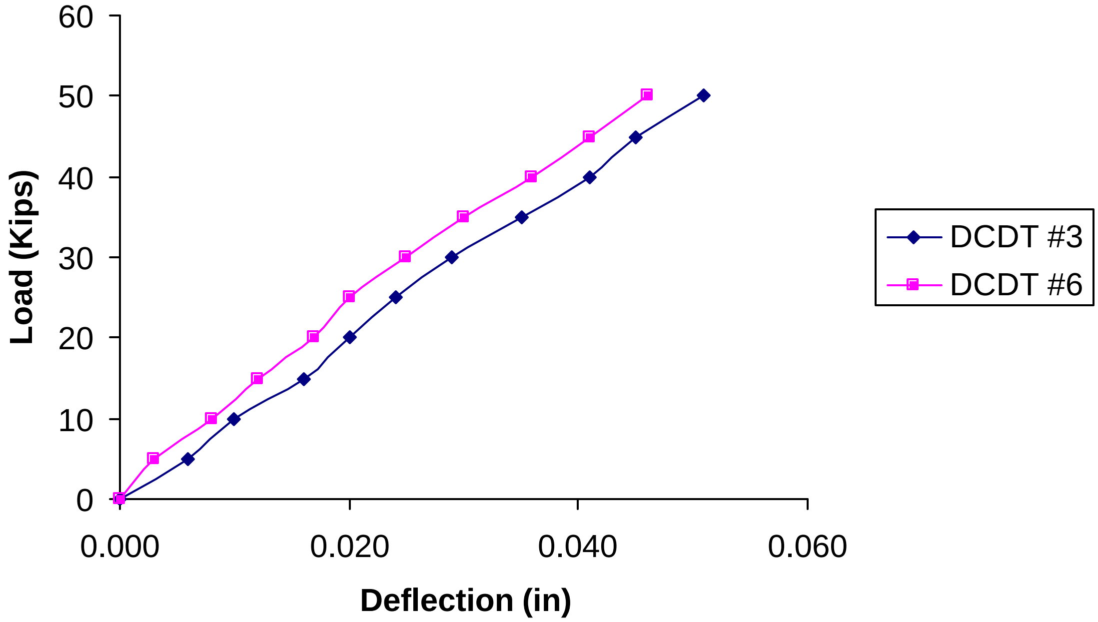

Figure B-258 Fatigue Specimen #2 Main Bar #1-600K Cycles

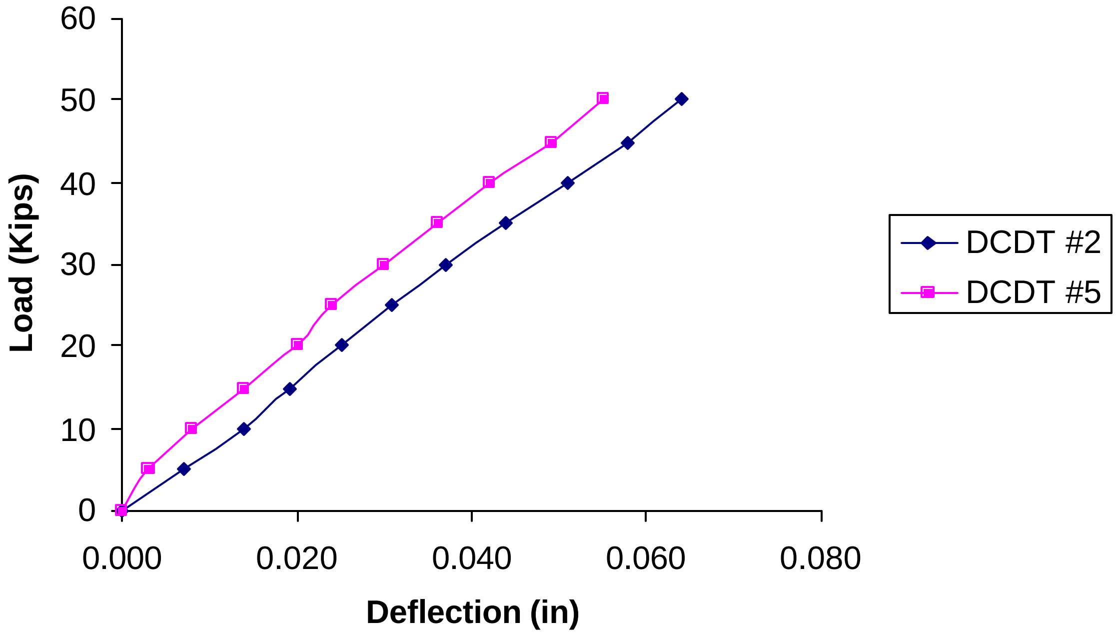

Figure B-259 Fatigue Specimen #2 Main Bar #2-600K Cycles

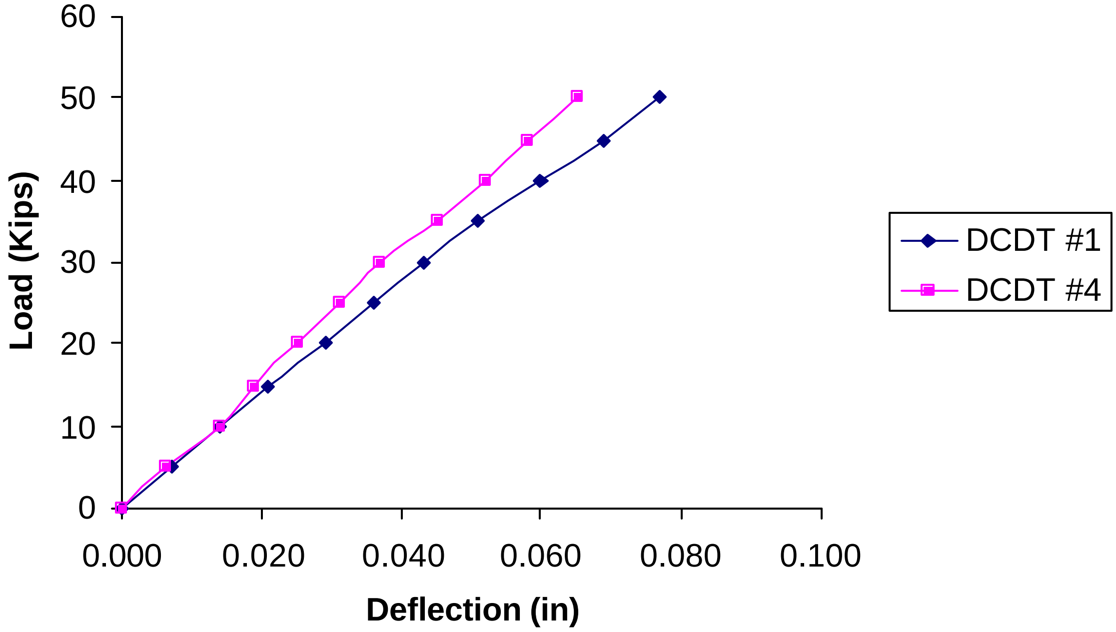

Figure B-260 Fatigue Specimen #2 Main Bar #3-600K Cycles

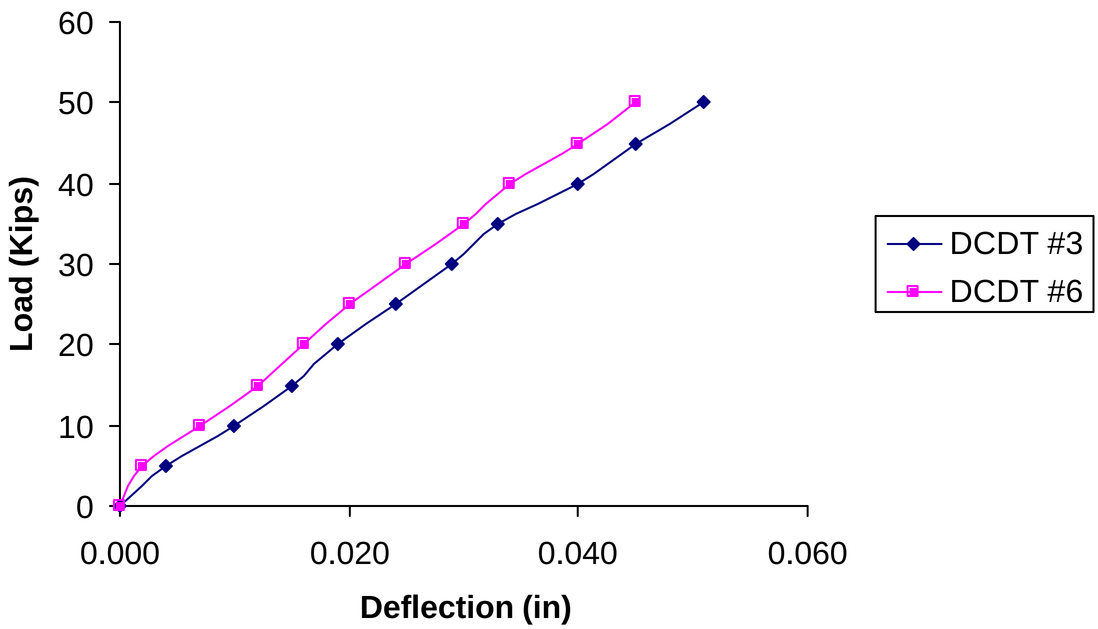

Figure B-261 Fatigue Specimen #2 Main Bar #1-750K Cycles

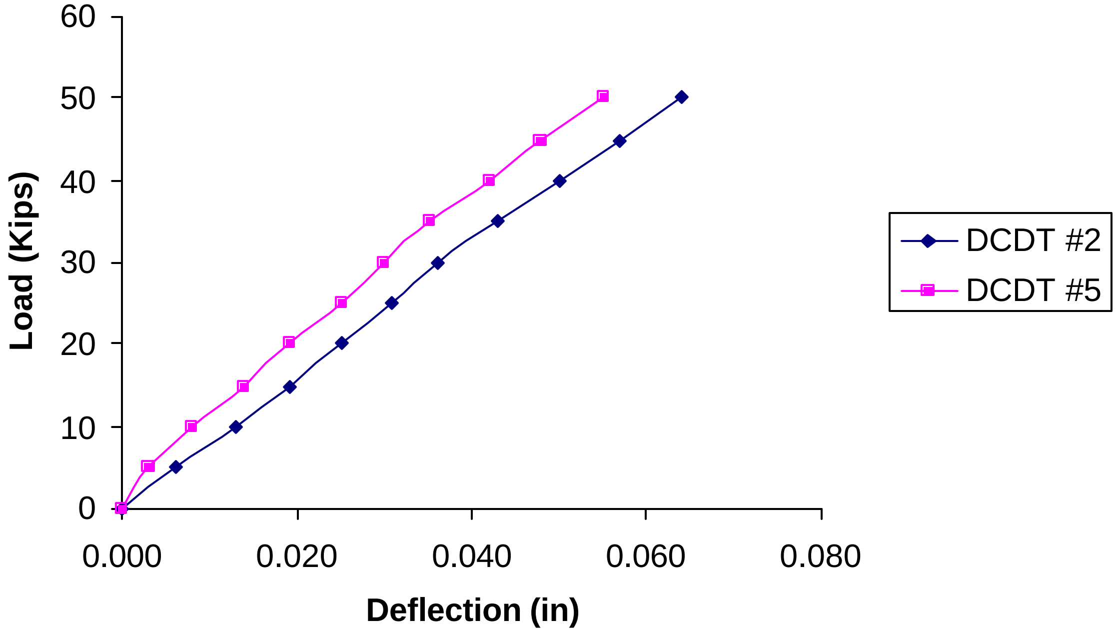

Figure B-262 Fatigue Specimen #2 Main Bar #2-750K Cycles

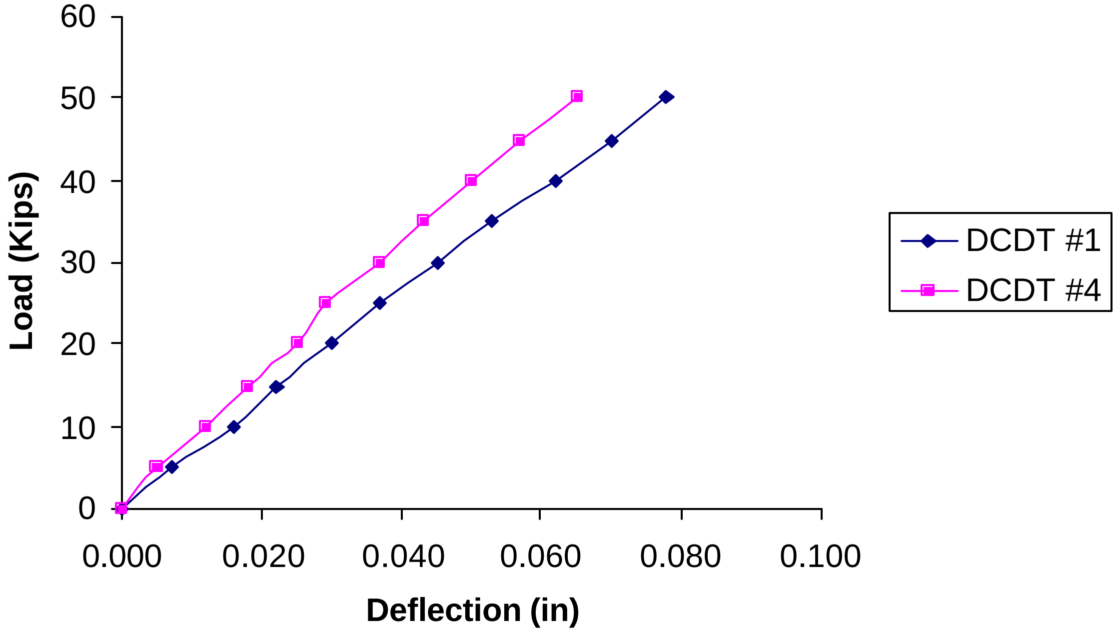

Figure B-263 Fatigue Specimen #2 Main Bar #3-750K Cycles

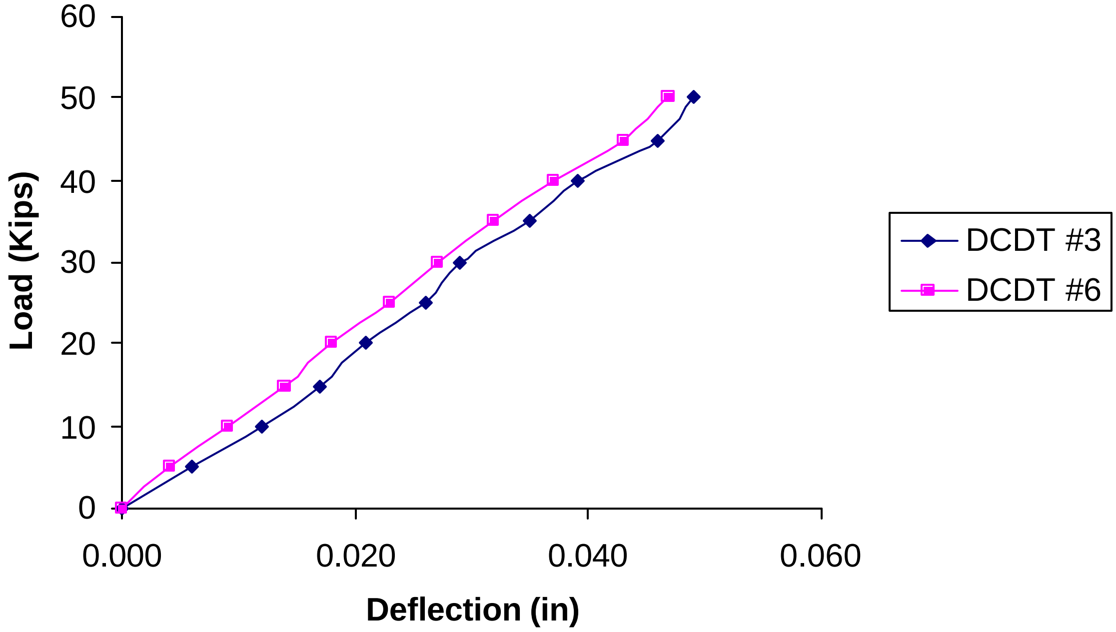

Figure B-264 Fatigue Specimen #2 Main Bar #1-900K Cycles

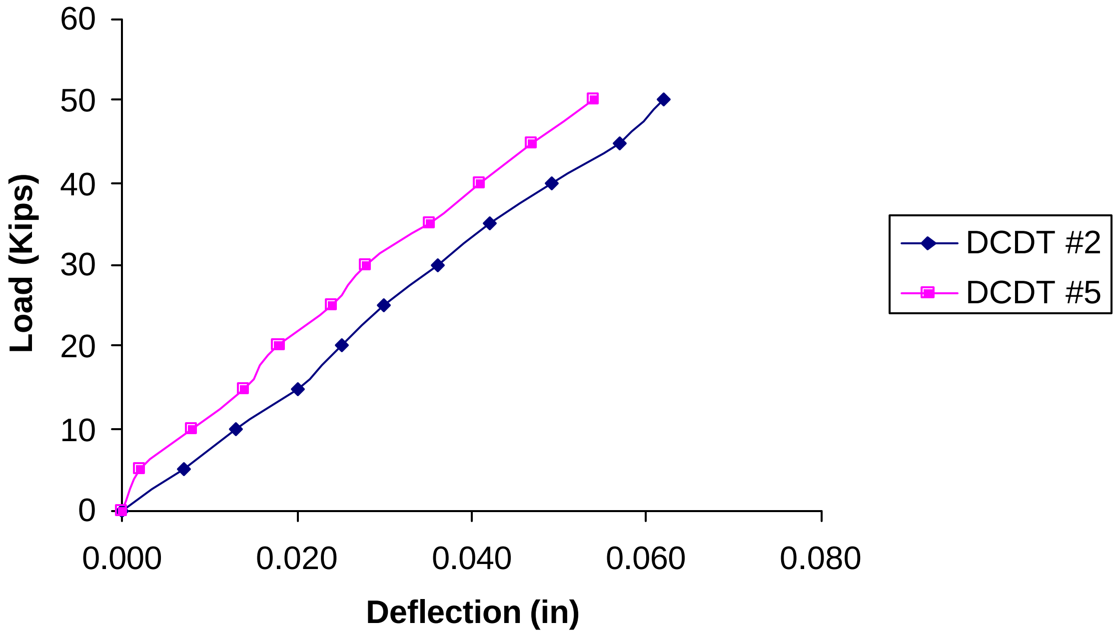

Figure B-265 Fatigue Specimen #2 Main Bar #2-900K Cycles

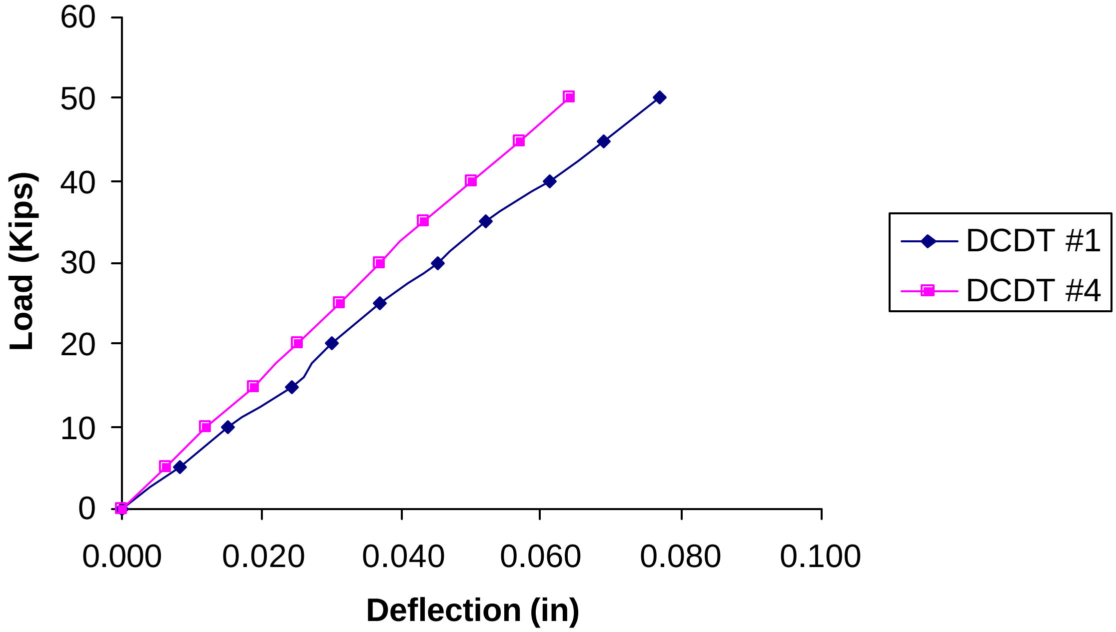

Figure B-266 Fatigue Specimen #2 Main Bar #3-900K Cycles

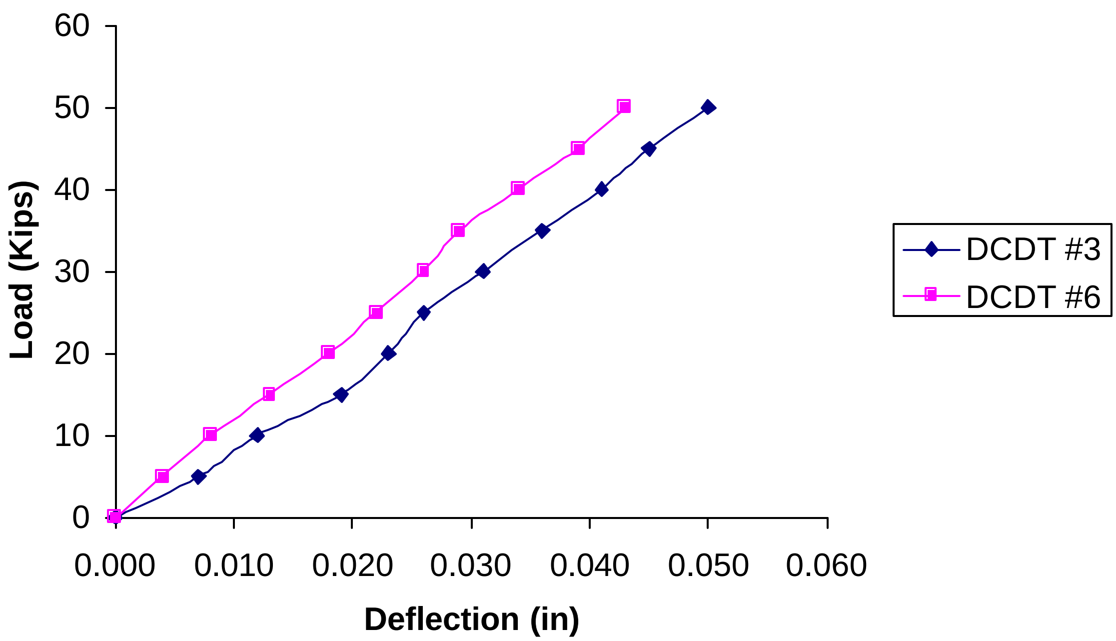

Figure B-267 Fatigue Specimen #2 Main Bar #1-1050K Cycles

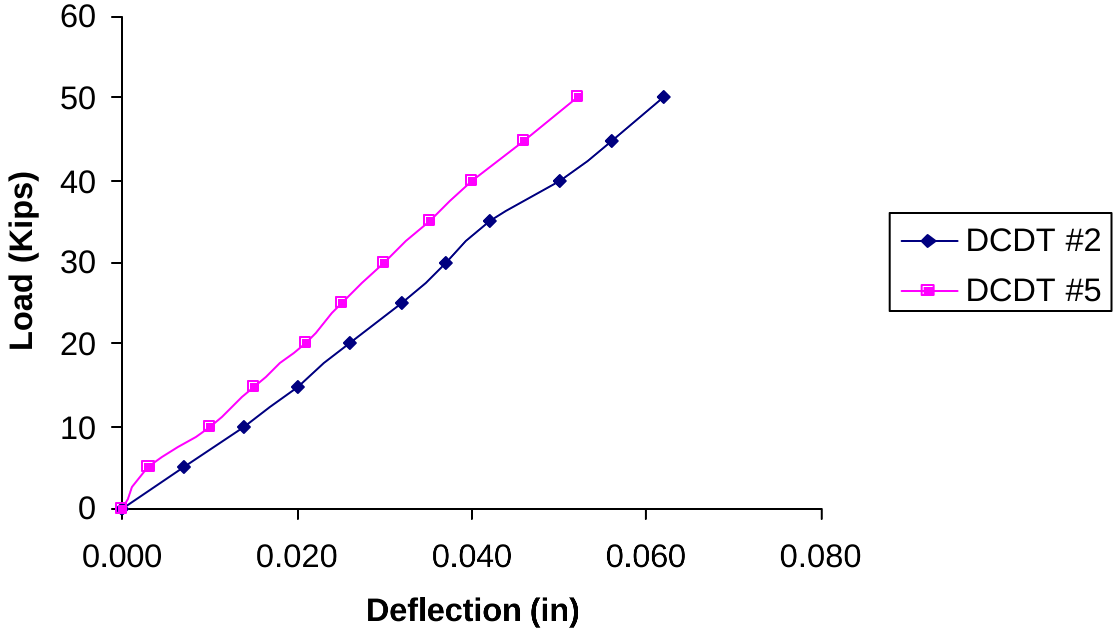

Figure B-268 Fatigue Specimen #2 Main Bar #2-1050K Cycles

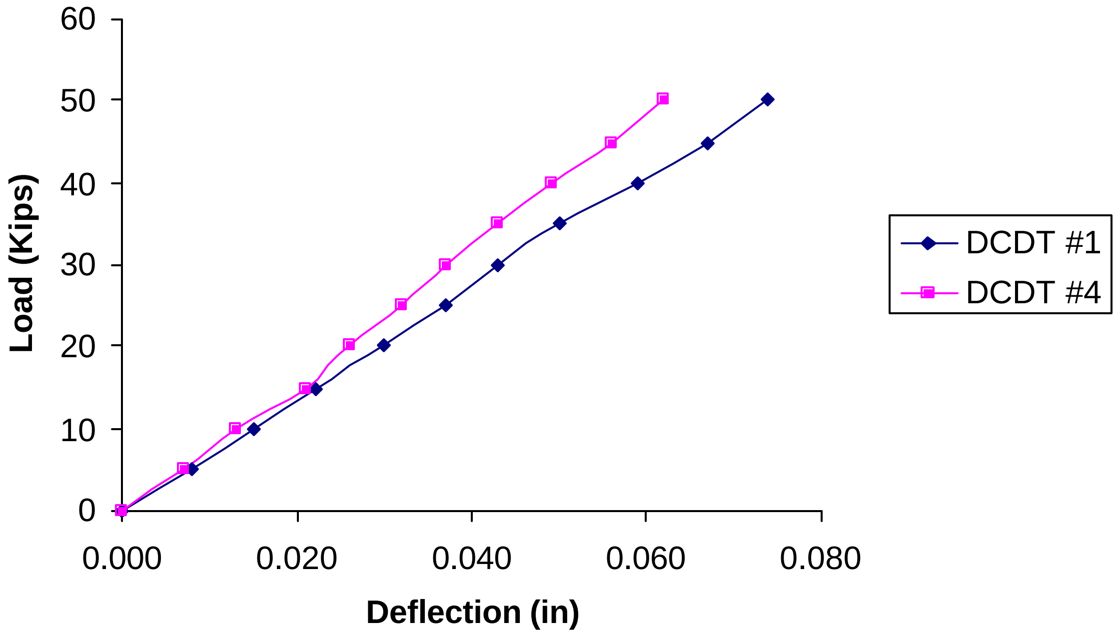

Figure B-269 Fatigue Specimen #2 Main Bar #3-1050K Cycles

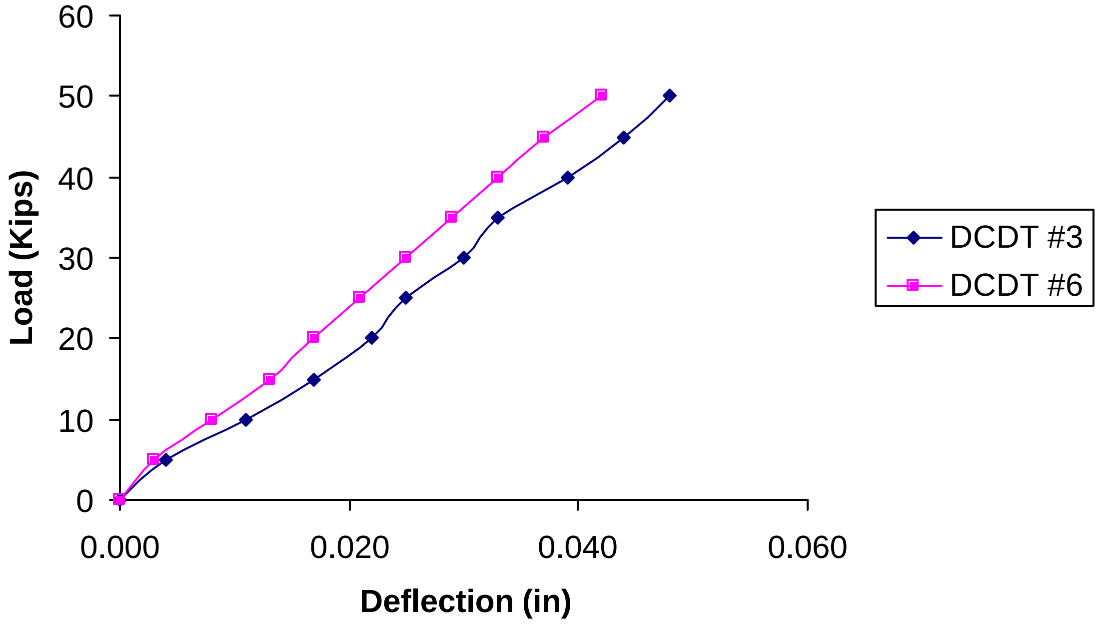

Figure B-270 Fatigue Specimen #2 Main Bar #1-1200K Cycles

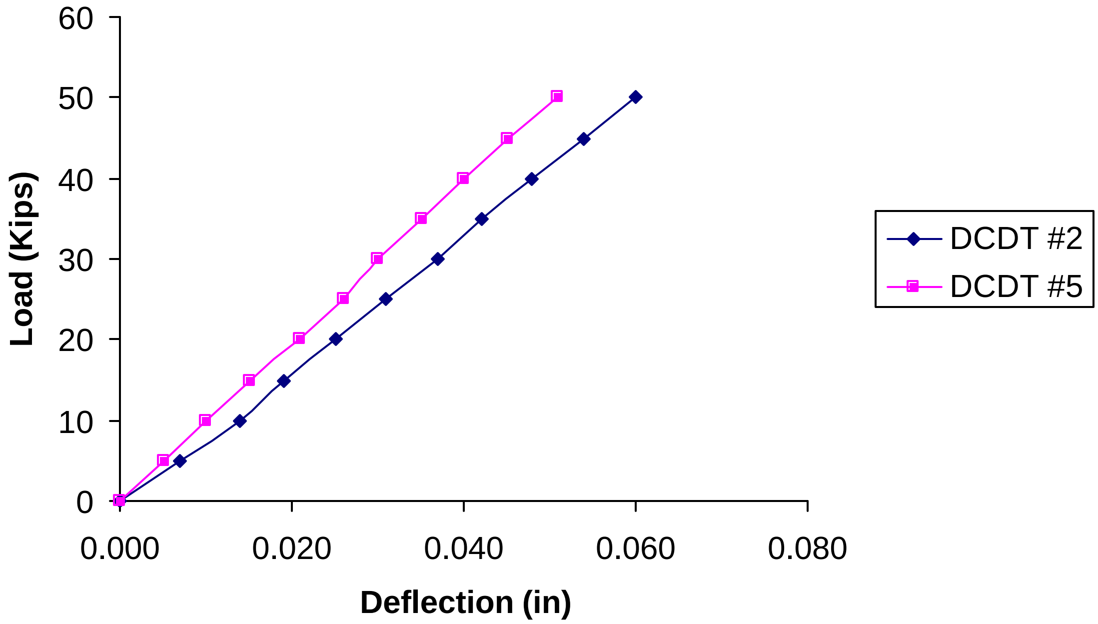

Figure B-271 Fatigue Specimen #2 Main Bar #2-1200K Cycles

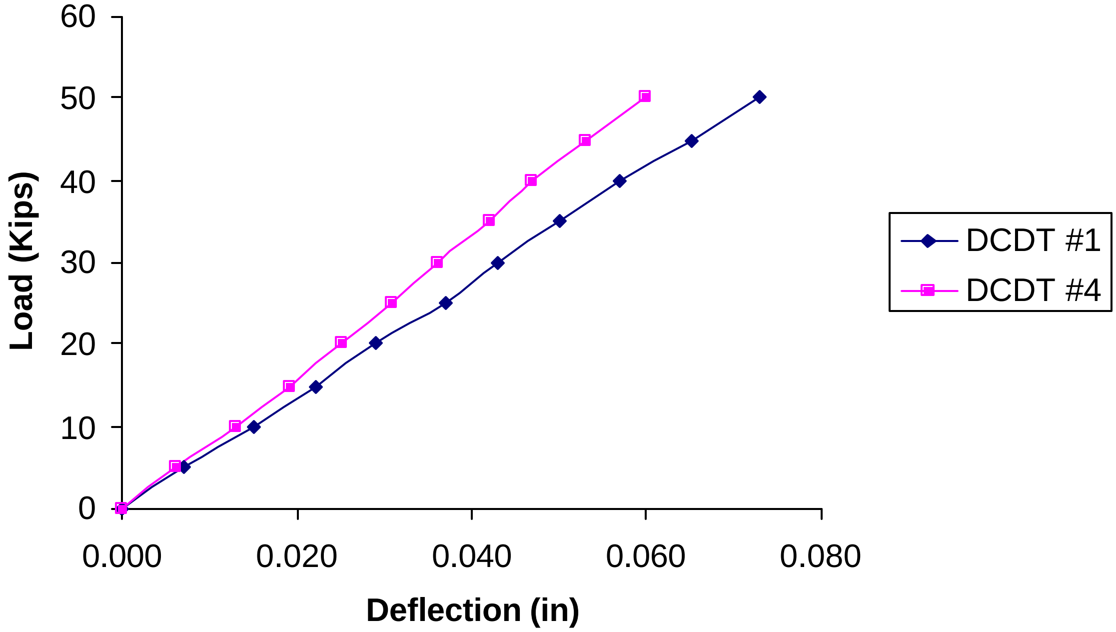

Figure B-272 Fatigue Specimen #2 Main Bar #3-1200K Cycles

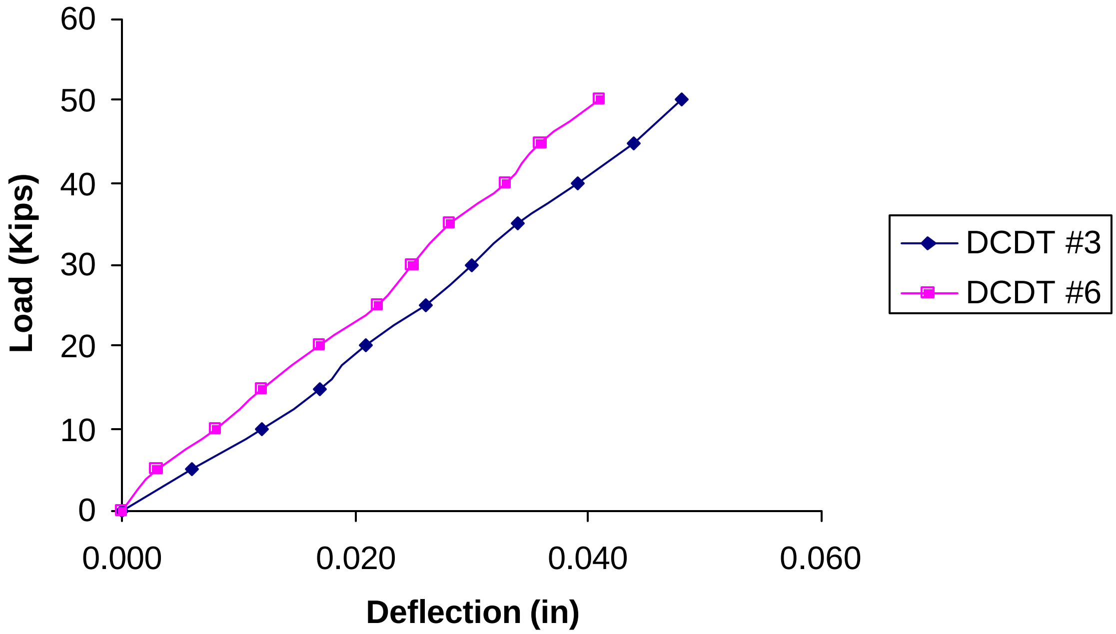

Figure B-273 Fatigue Specimen #2 Main Bar #1-1350K Cycles

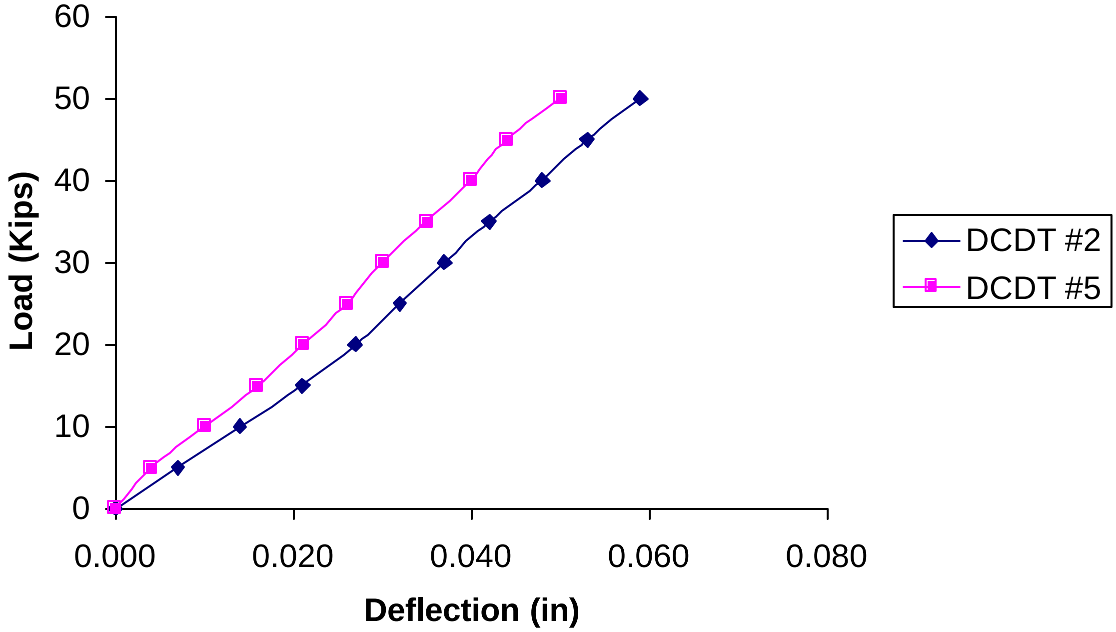

Figure B-274 Fatigue Specimen #2 Main Bar #2-1350K Cycles

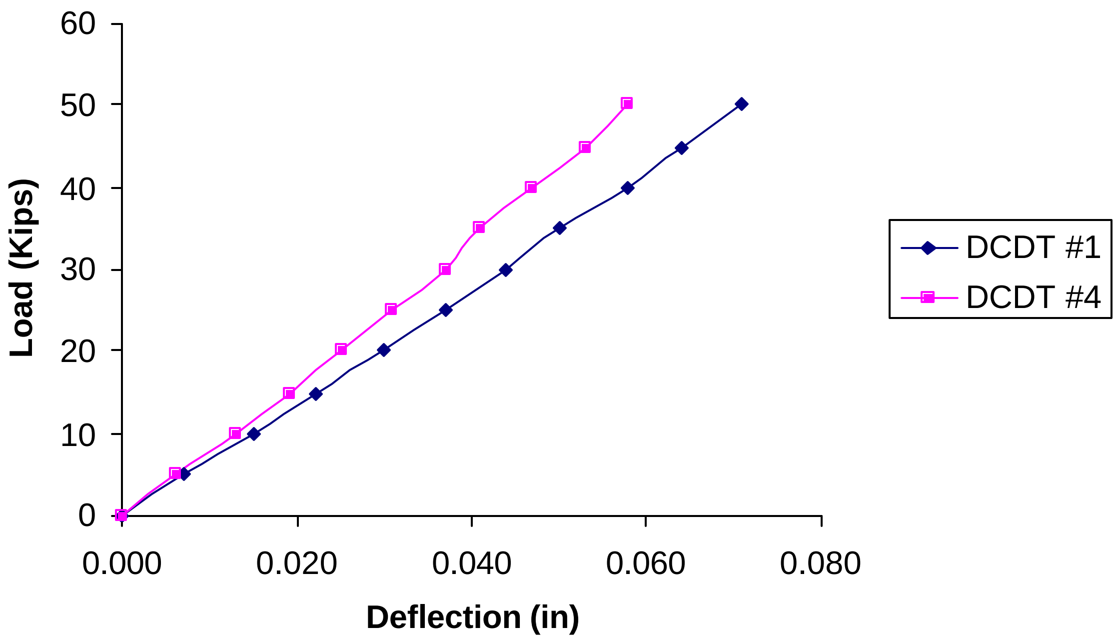

Figure B-275 Fatigue Specimen #2 Main Bar #3-1350K Cycles

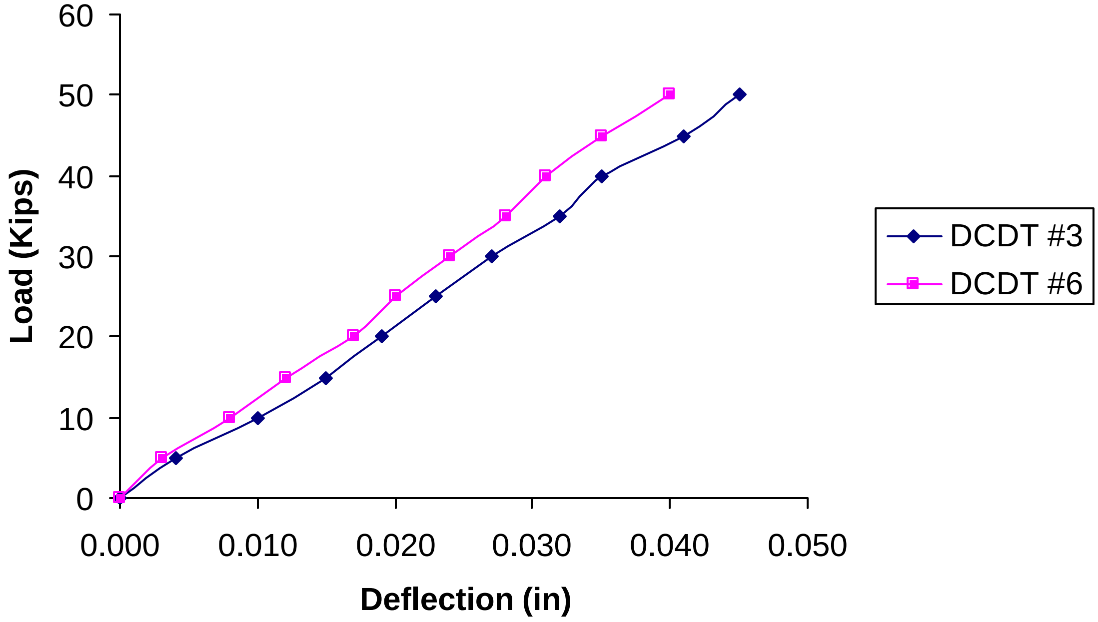

Figure B-276 Fatigue Specimen #2 Main Bar #1-1500K Cycles

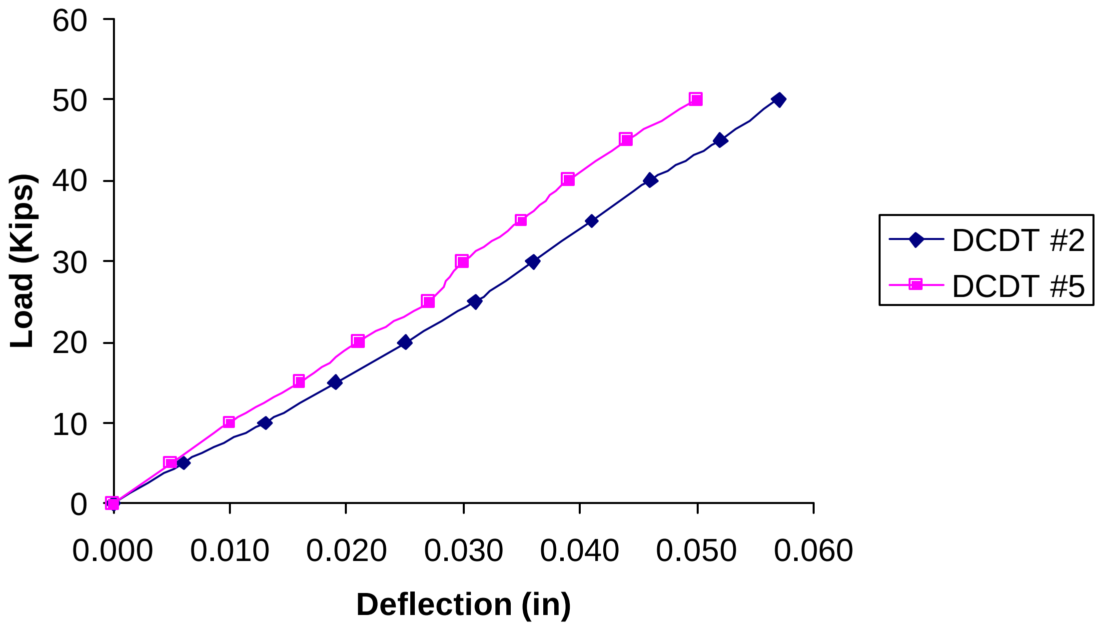

Figure B-277 Fatigue Specimen #2 Main Bar #2-1500K Cycles

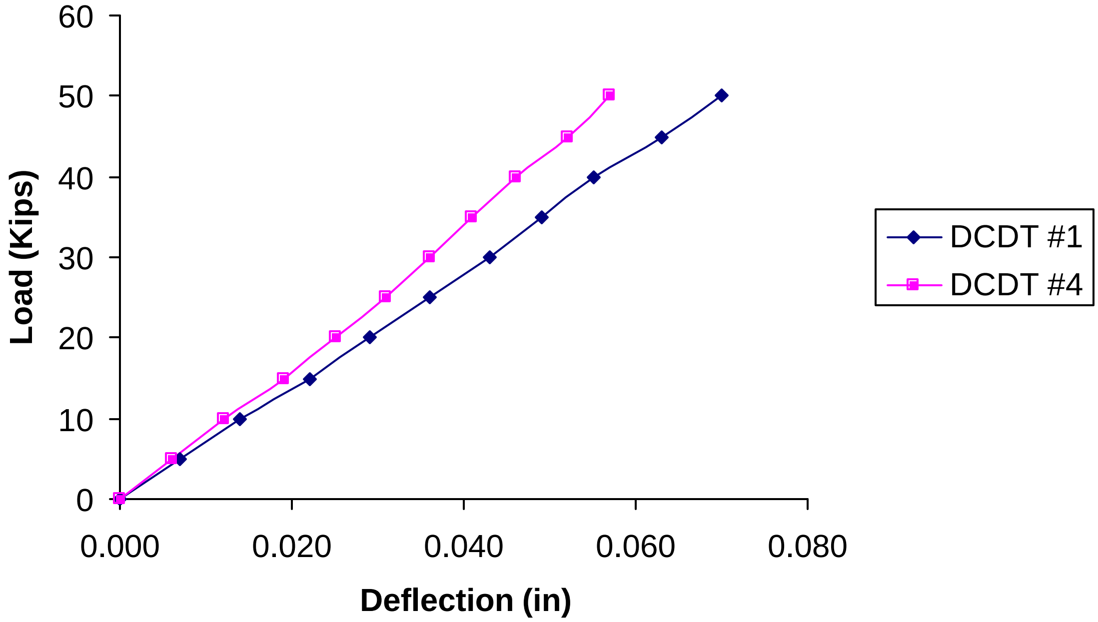

Figure B-278 Fatigue Specimen #2 Main Bar #3-1500K Cycles

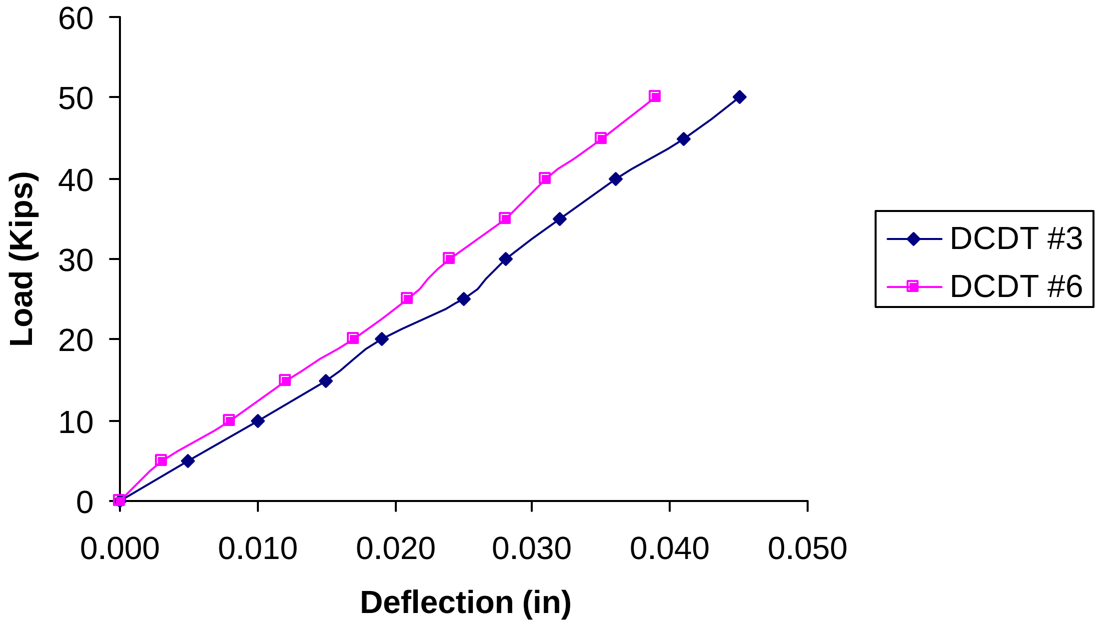

Figure B-279 Fatigue Specimen #2 Main Bar #1-1700K Cycles

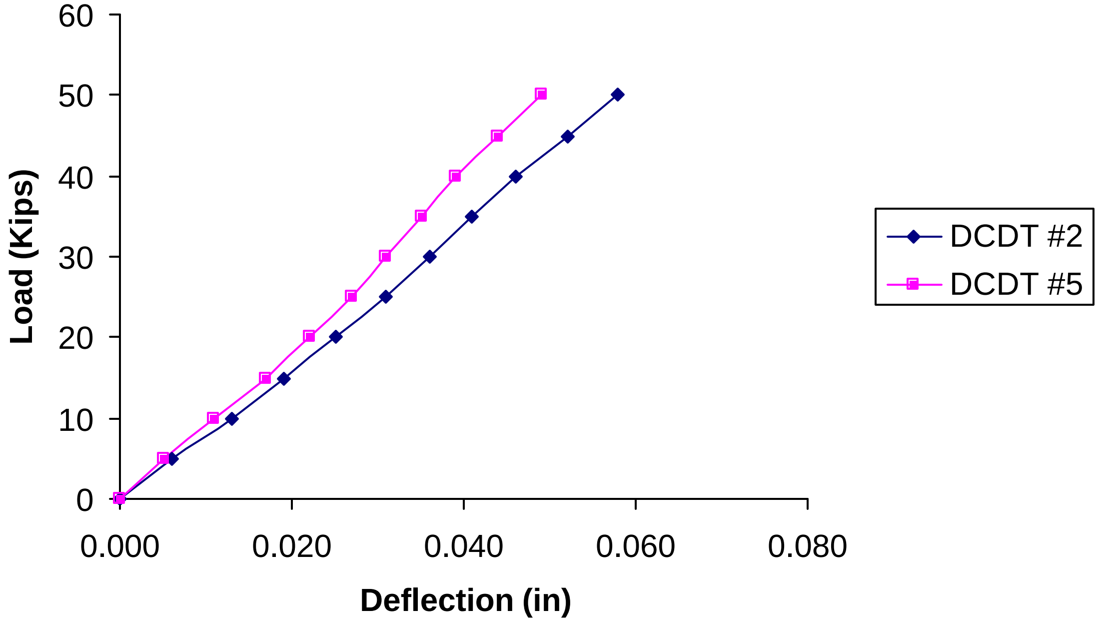

Figure B-280 Fatigue Specimen #2 Main Bar #2-1700K Cycles

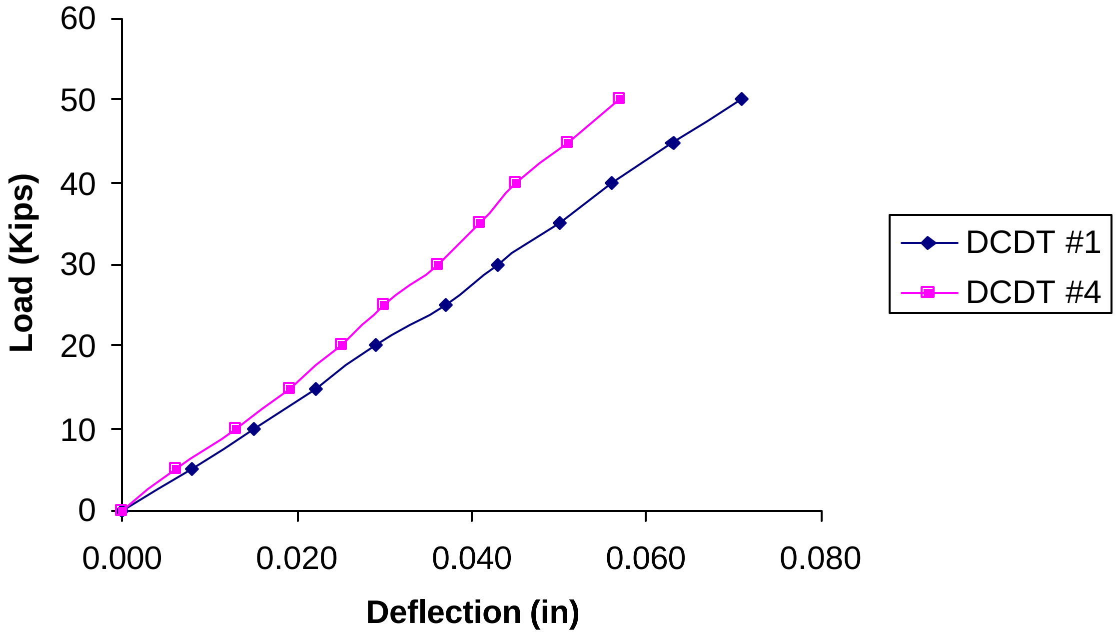

Figure B-281 Fatigue Specimen #2 Main Bar #3-1700K Cycles

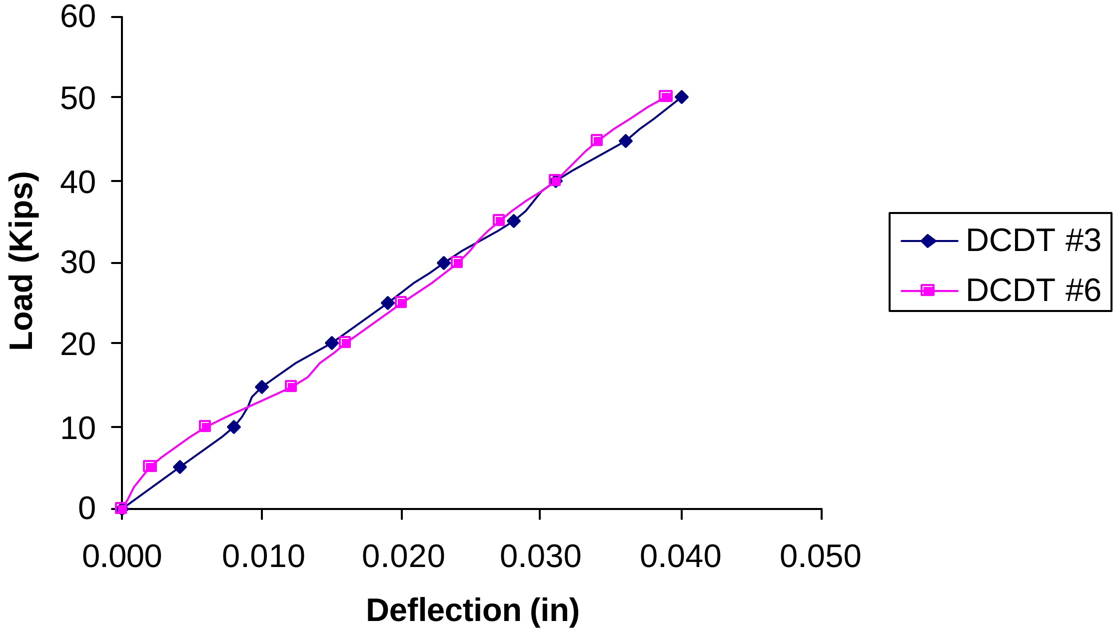

Figure B-282 Fatigue Specimen #2 Main Bar #1-1850K Cycles

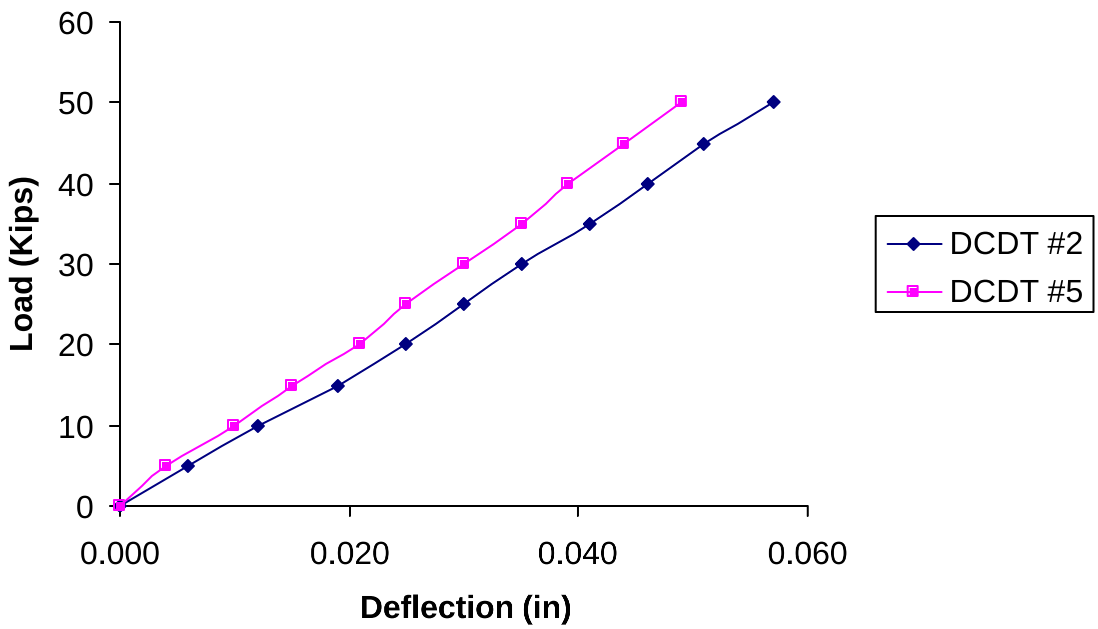

Figure B-283 Fatigue Specimen #2 Main Bar #2-1850K Cycles

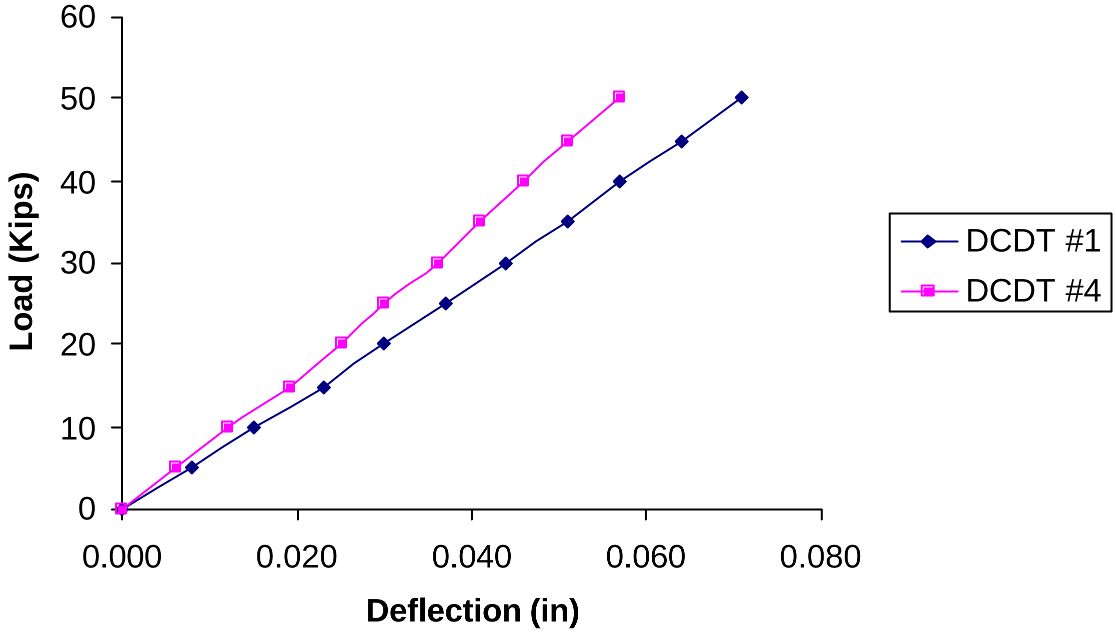

Figure B-284 Fatigue Specimen #2 Main Bar #3-1850K Cycles

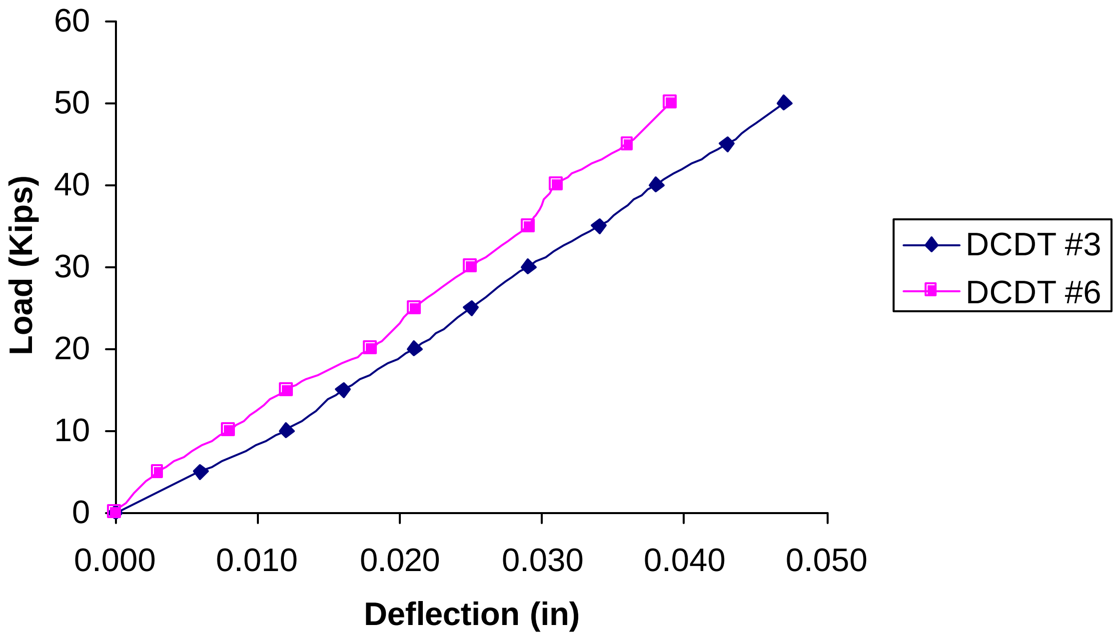

Figure B-285 Fatigue Specimen #2 Main Bar #1-2000K Cycles

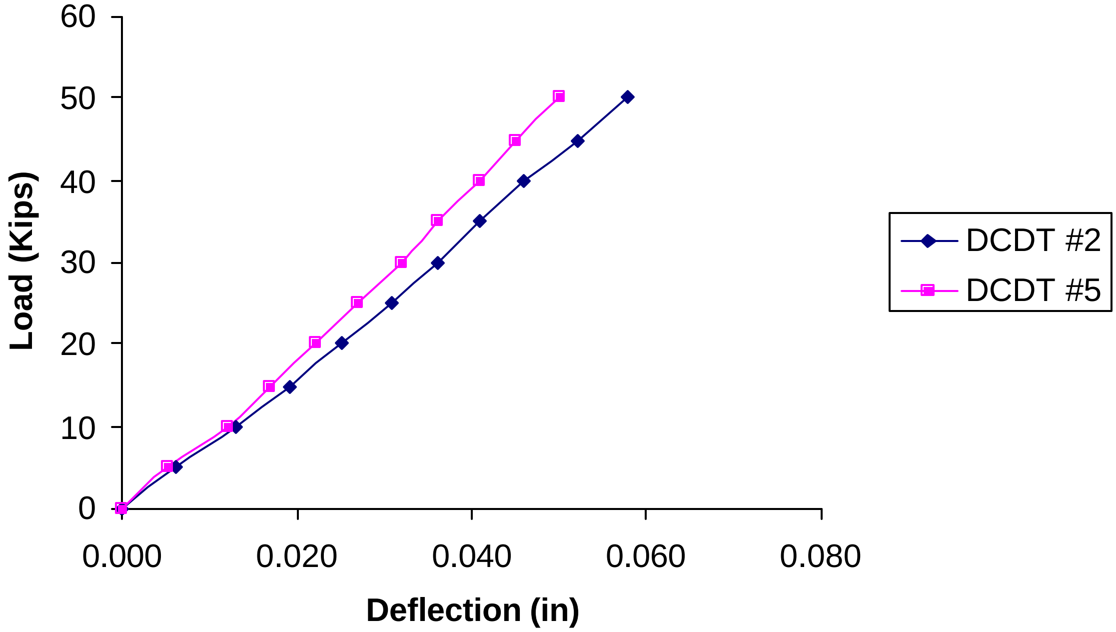

Figure B-286 Fatigue Specimen #2 Main Bar #2-2000K Cycles

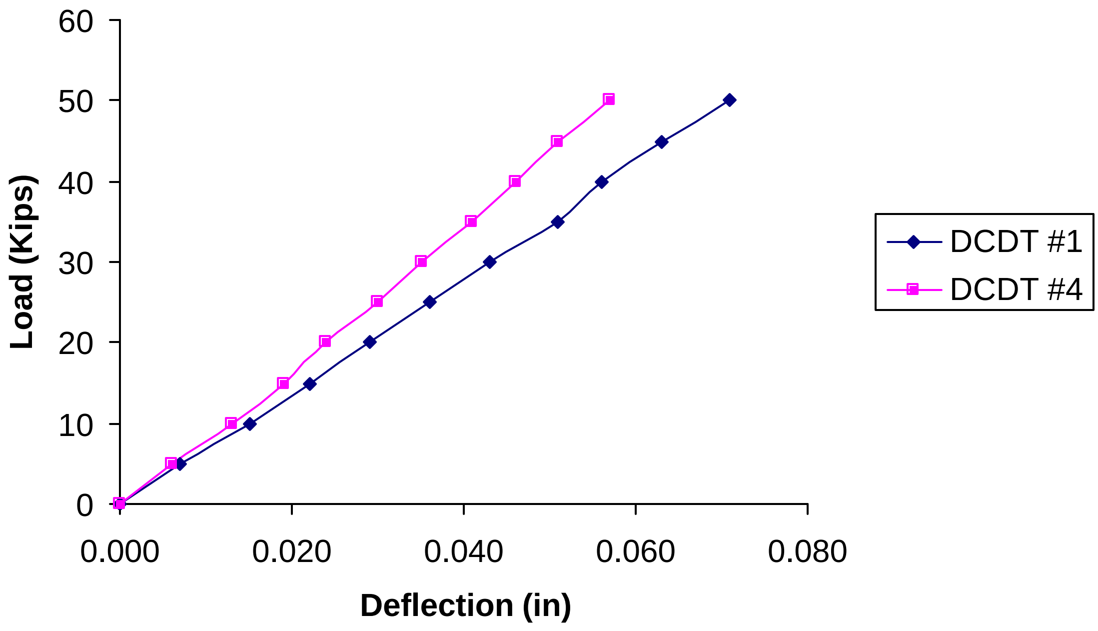

Figure B-287 Fatigue Specimen #2 Main Bar #3-2000K Cycles

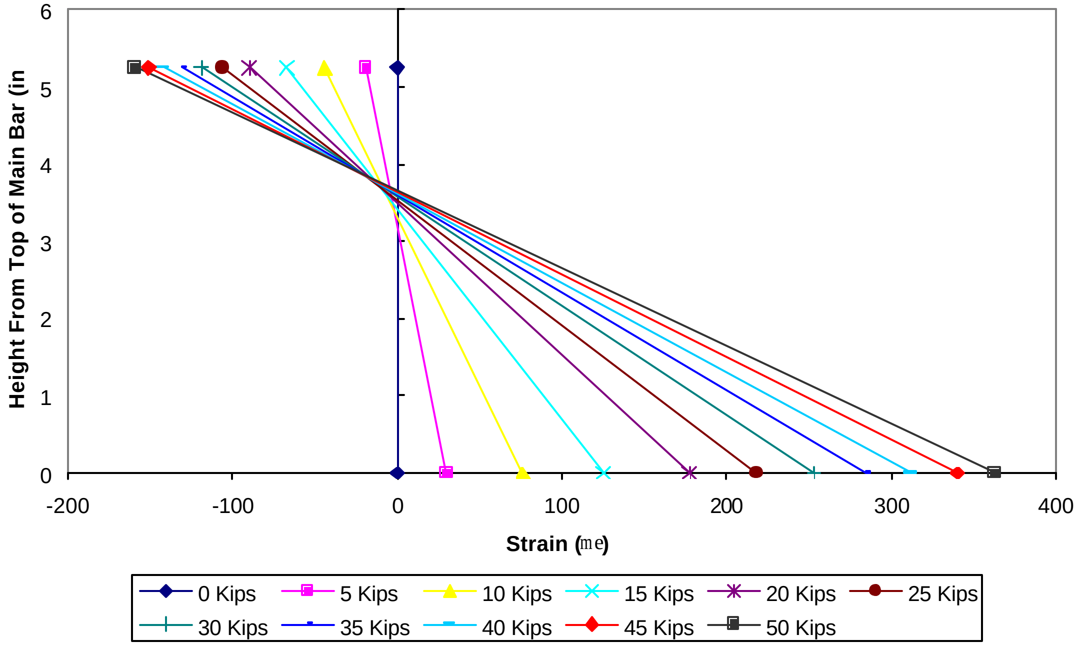

Figure B-288 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-Benchmark

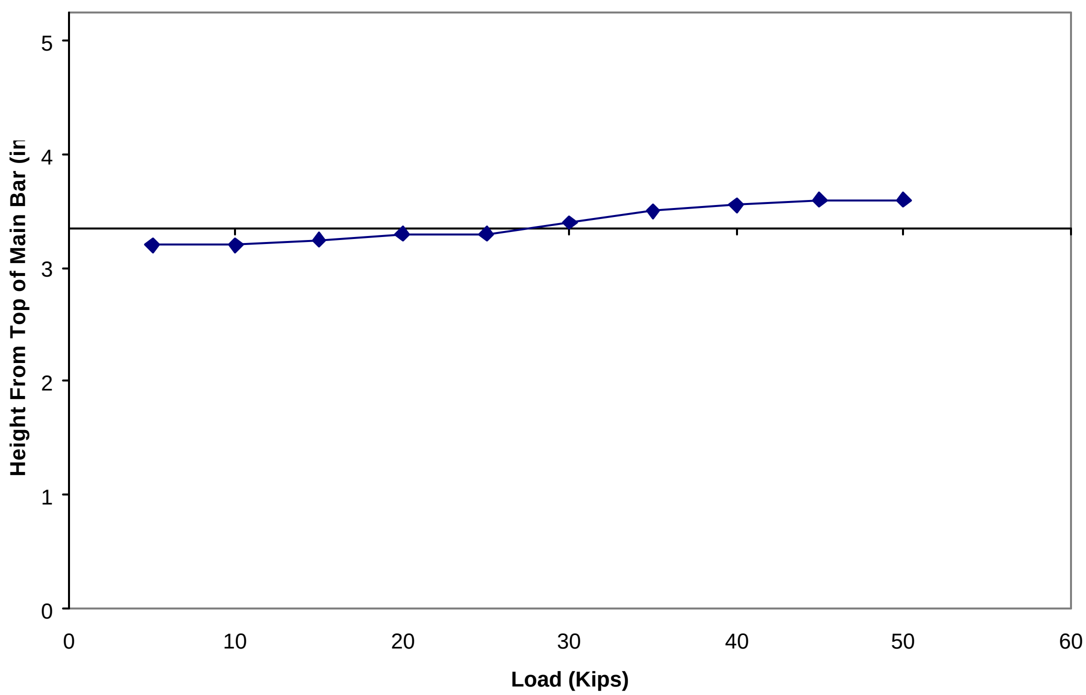

Figure B-289 Fatigue Specimen #2 Main Bar #1
- Neutral Axis Location-Benchmark

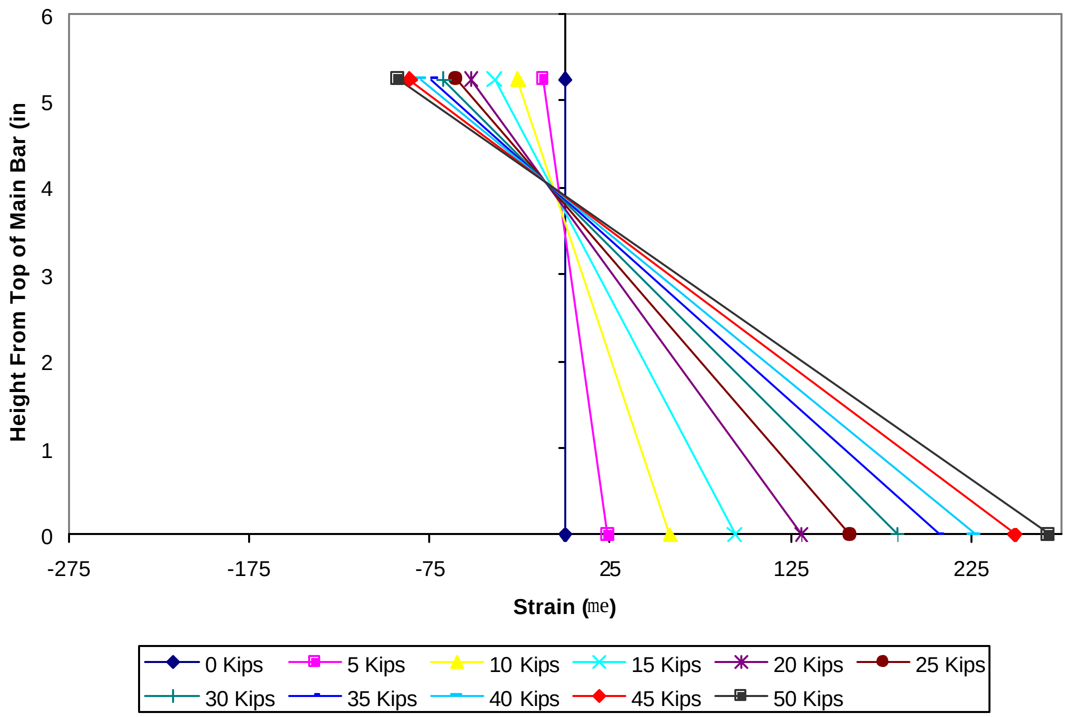

Figure B-290 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-Benchmark

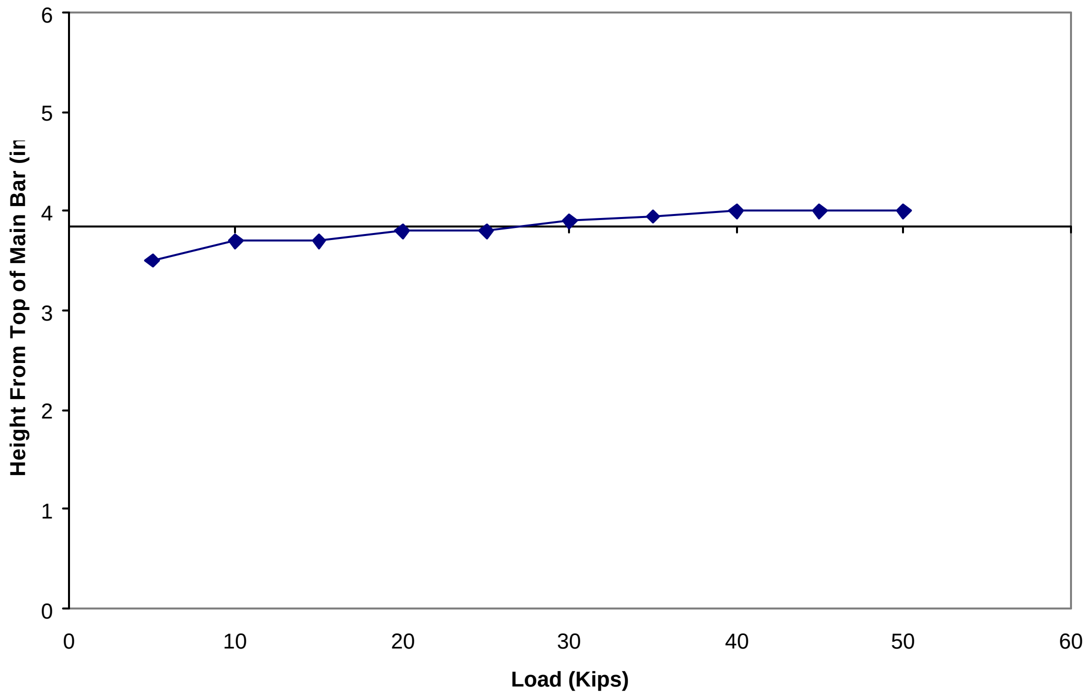

Figure B-291 Fatigue Specimen #2 Main Bar #2
- Neutral Axis Location-Benchmark

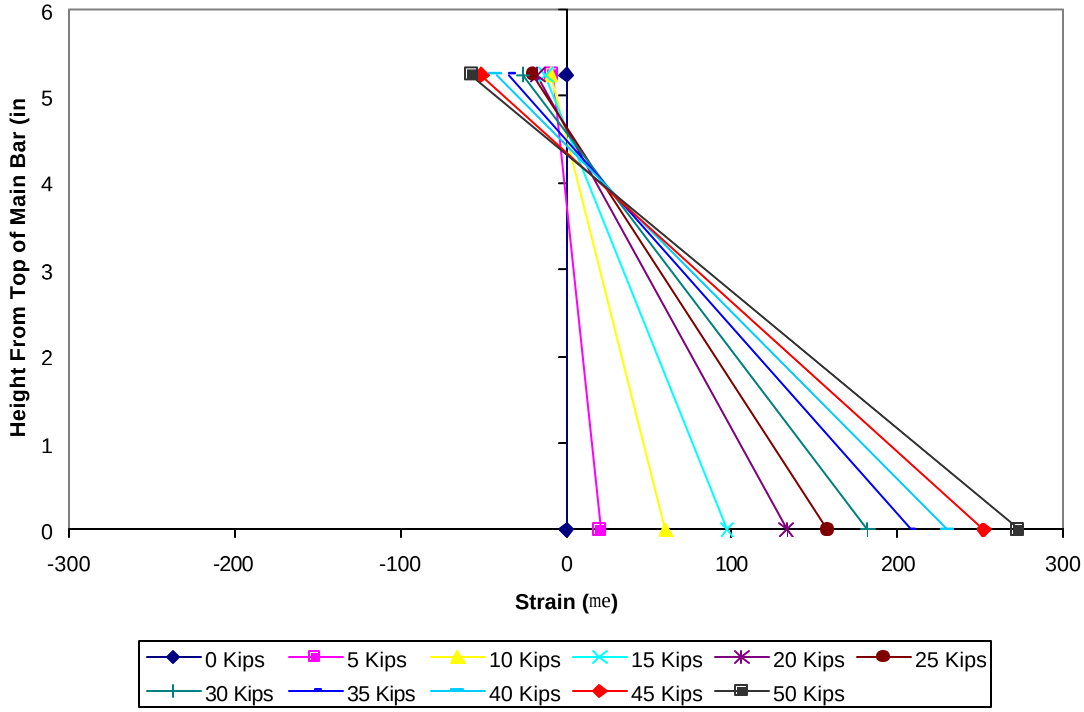

Figure B-292 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-Benchmark

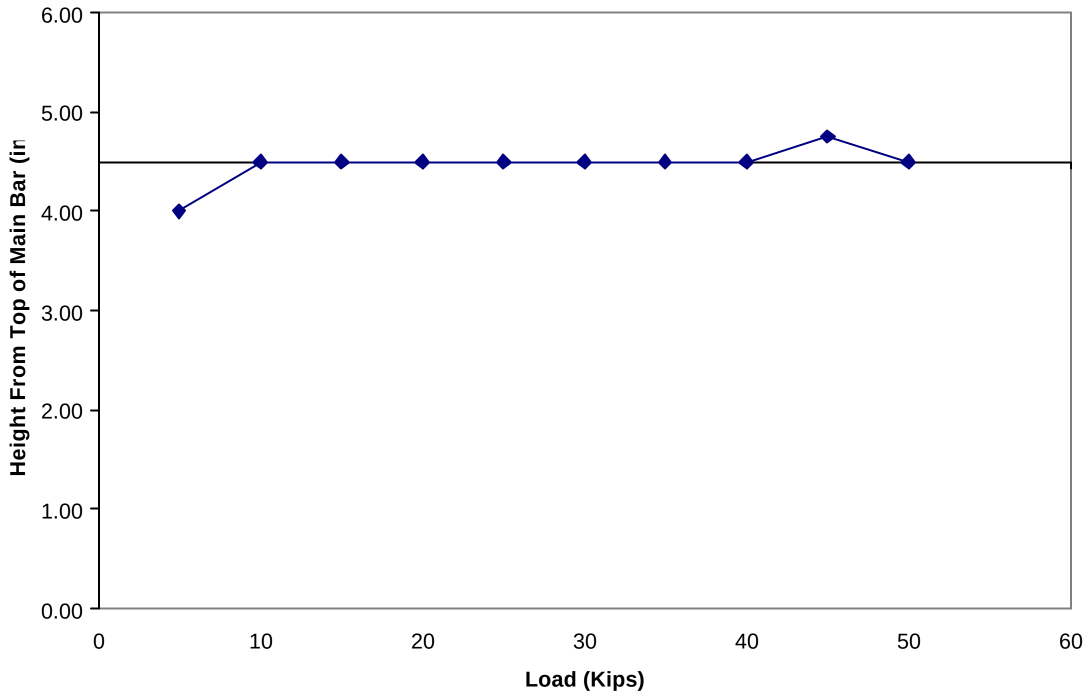

Figure B-293 Fatigue Specimen #2 Main Bar #3
- Neutral Axis Location-Benchmark

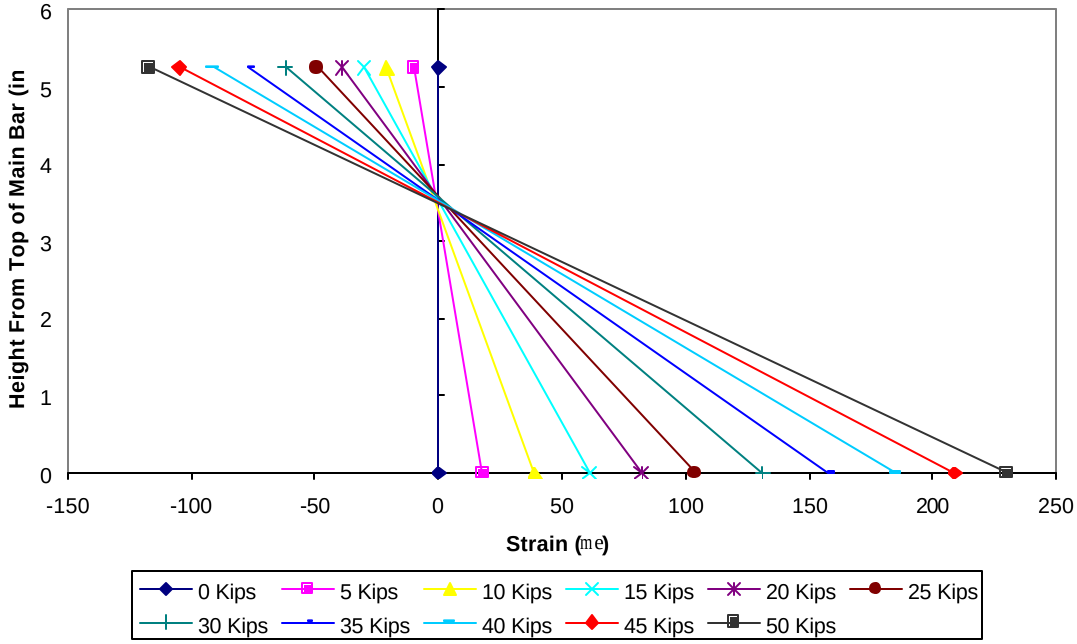

Figure B-294 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-150K Cycles

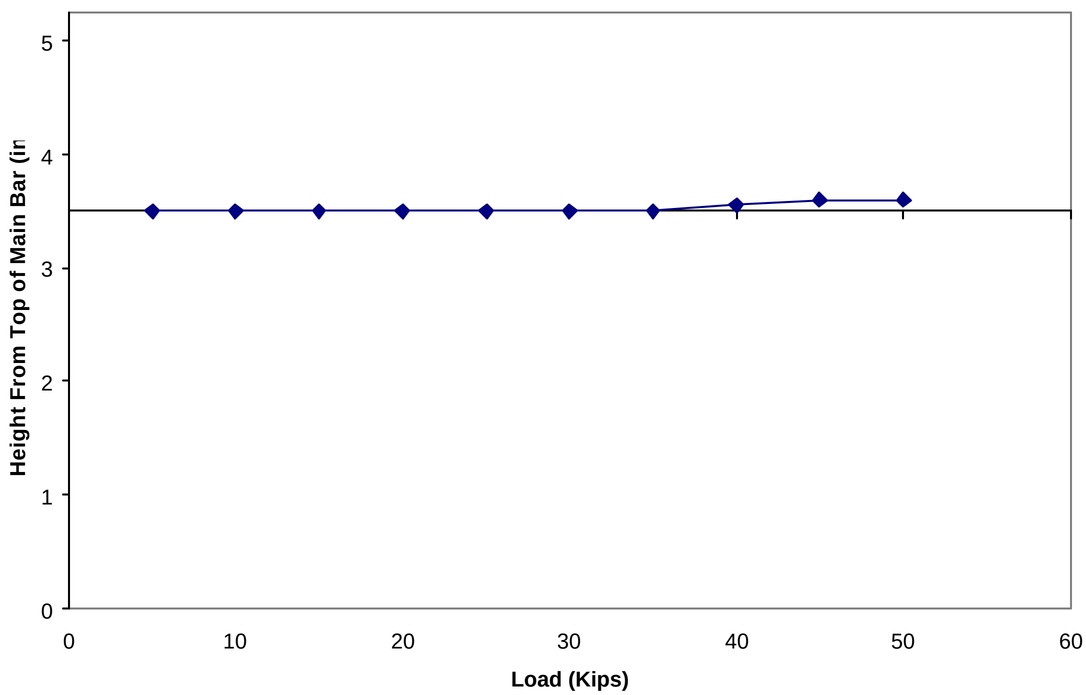

Figure B-295 Fatigue Specimen #2 Main Bar #1
- Neutral Axis Location-150K Cycles

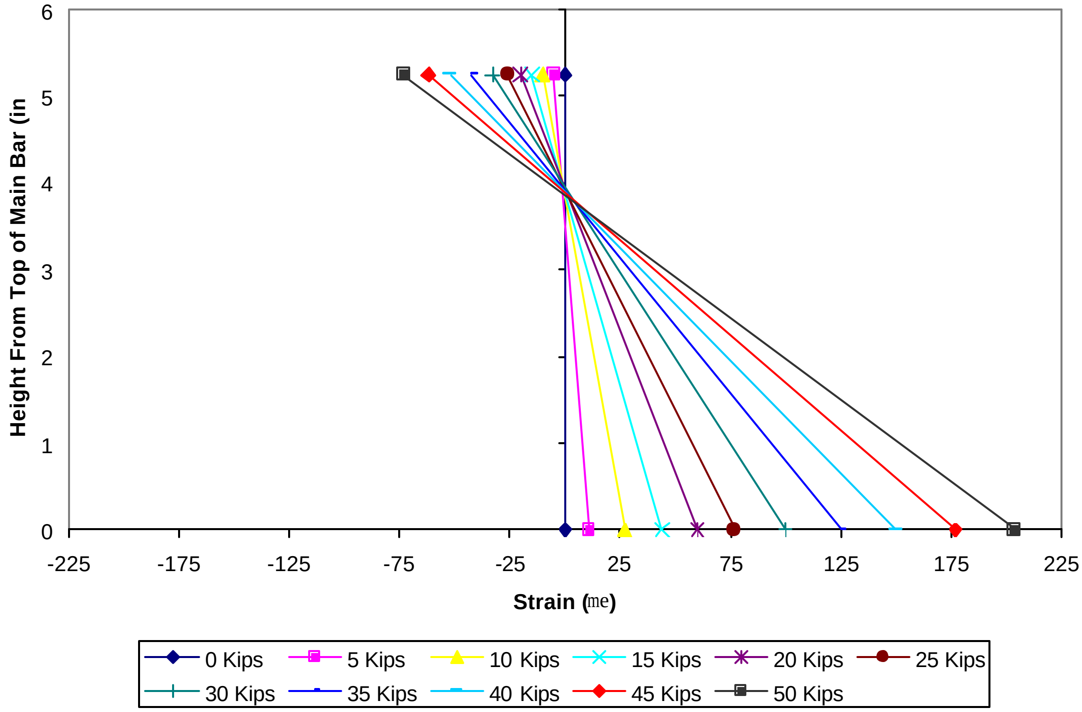

Figure B-296 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-150K Cycles

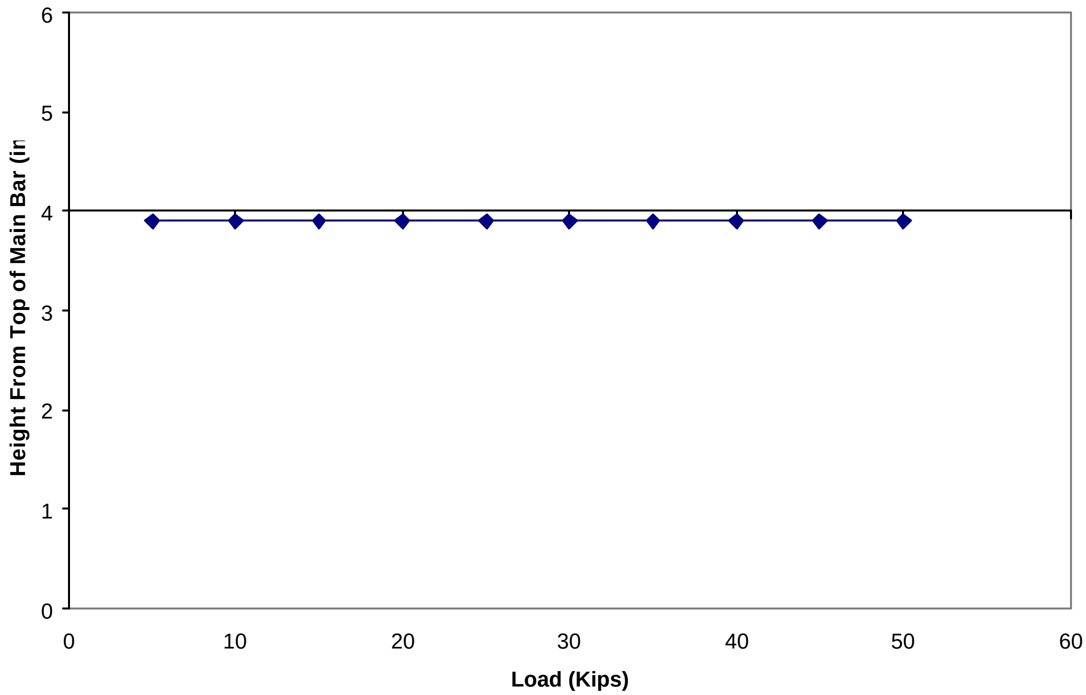

Figure B-297 Fatigue Specimen #2 Main Bar #2
- Neutral Axis Location-150K Cycles

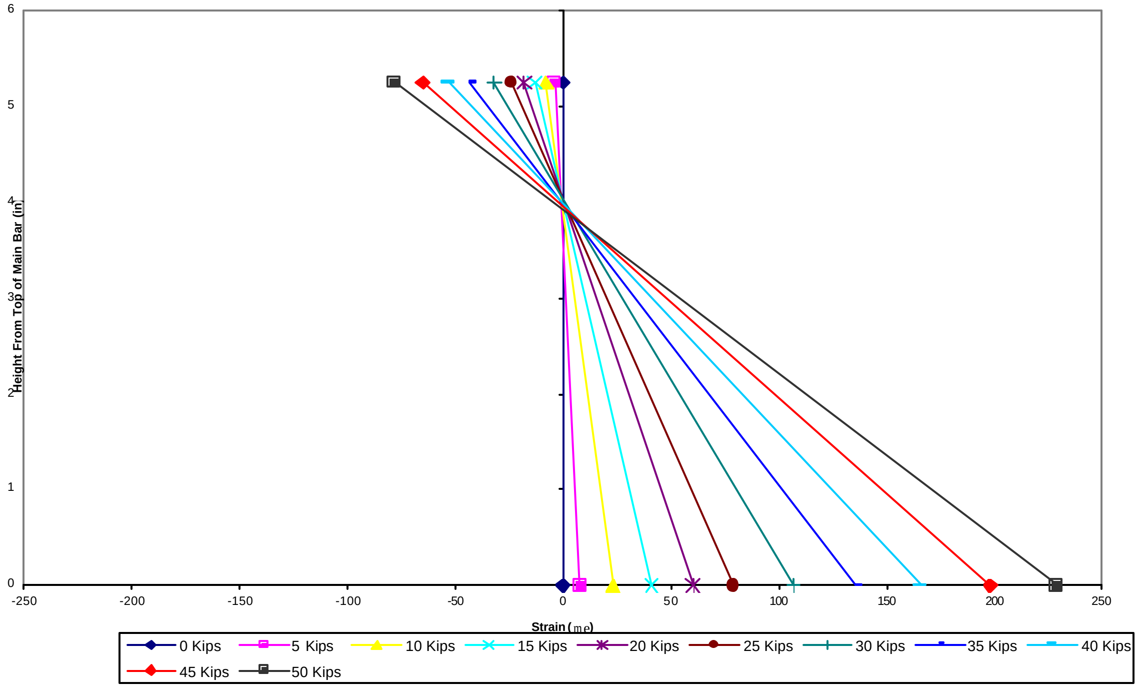

Figure B-298 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-150K Cycles

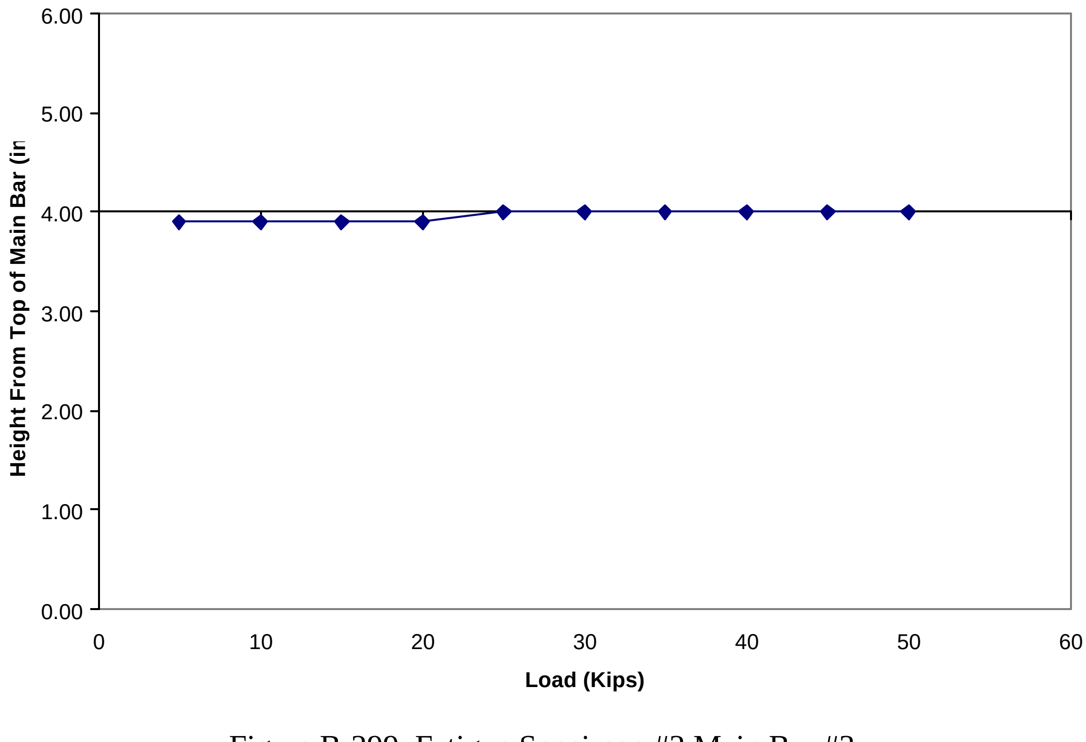

Figure B-299 Fatigue Specimen #2 Main Bar #3
- Neutral Axis Location-150K Cycles

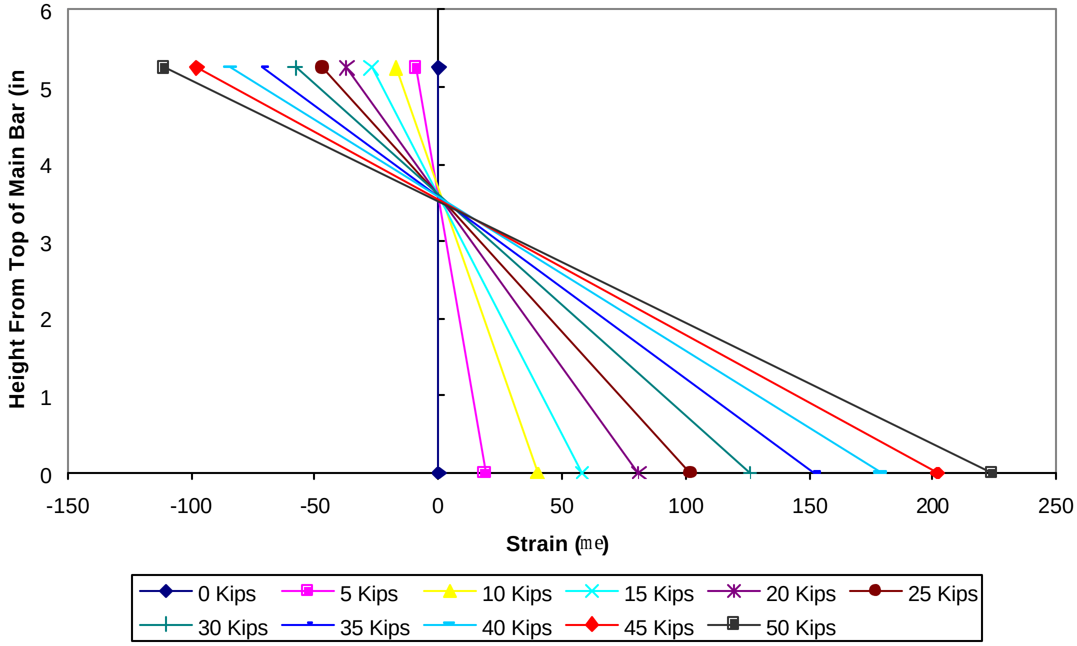

Figure B-300 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-300K Cycles

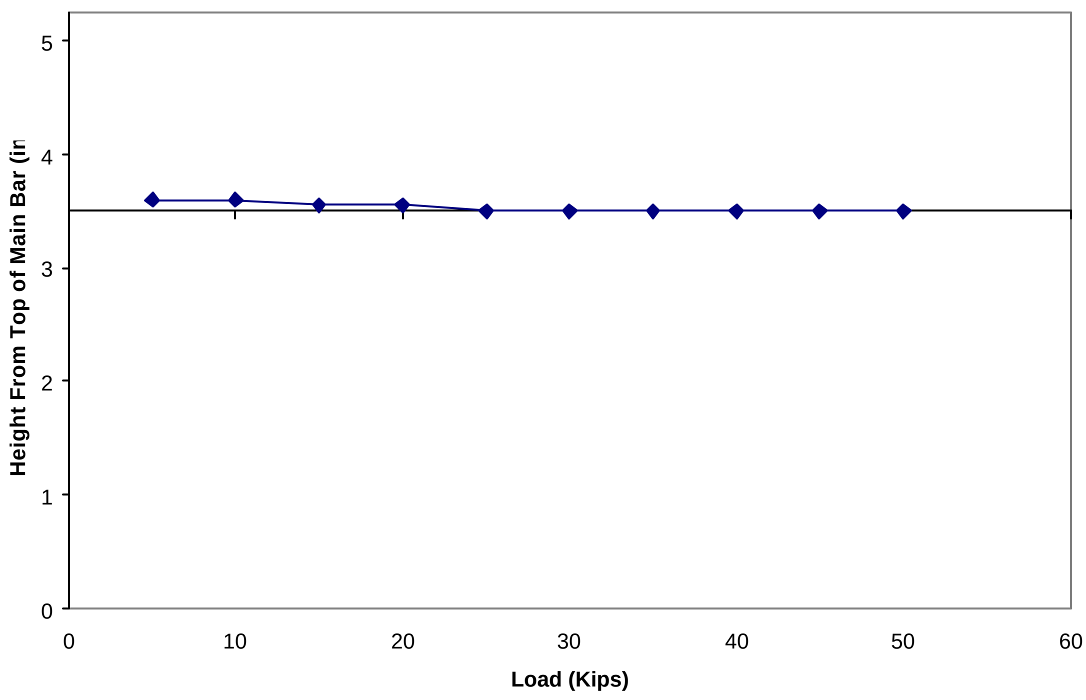

Figure B-301 Fatigue Specimen #2 Main Bar #1
- Neutral Axis Location-300K Cycles

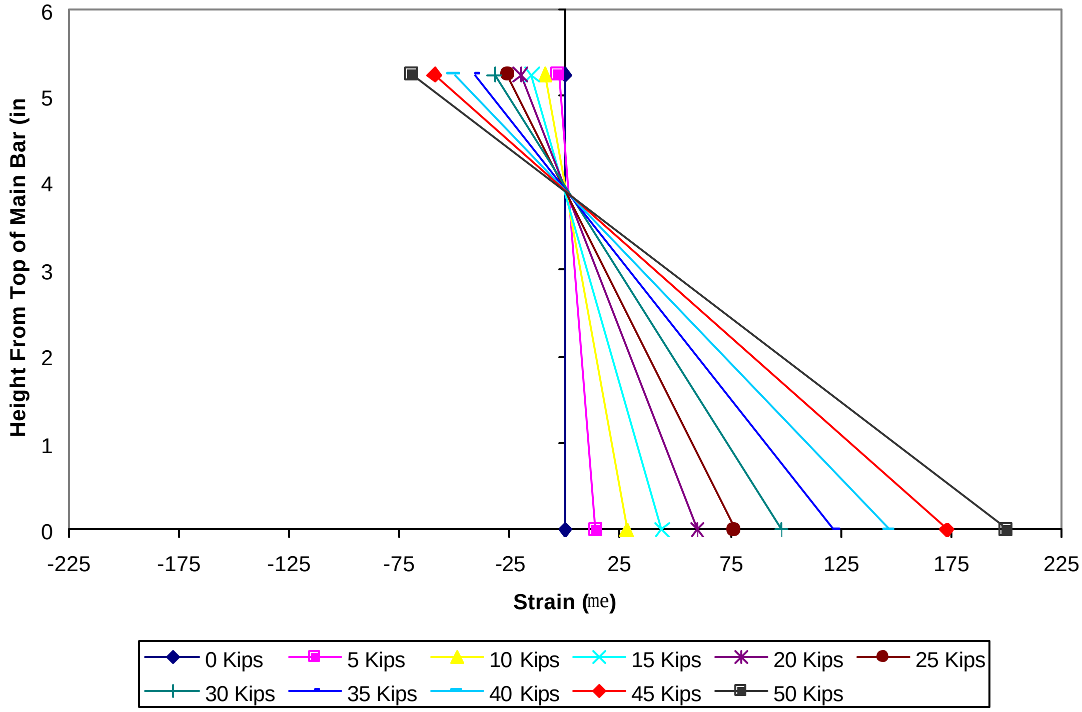

Figure B-302 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-300K Cycles

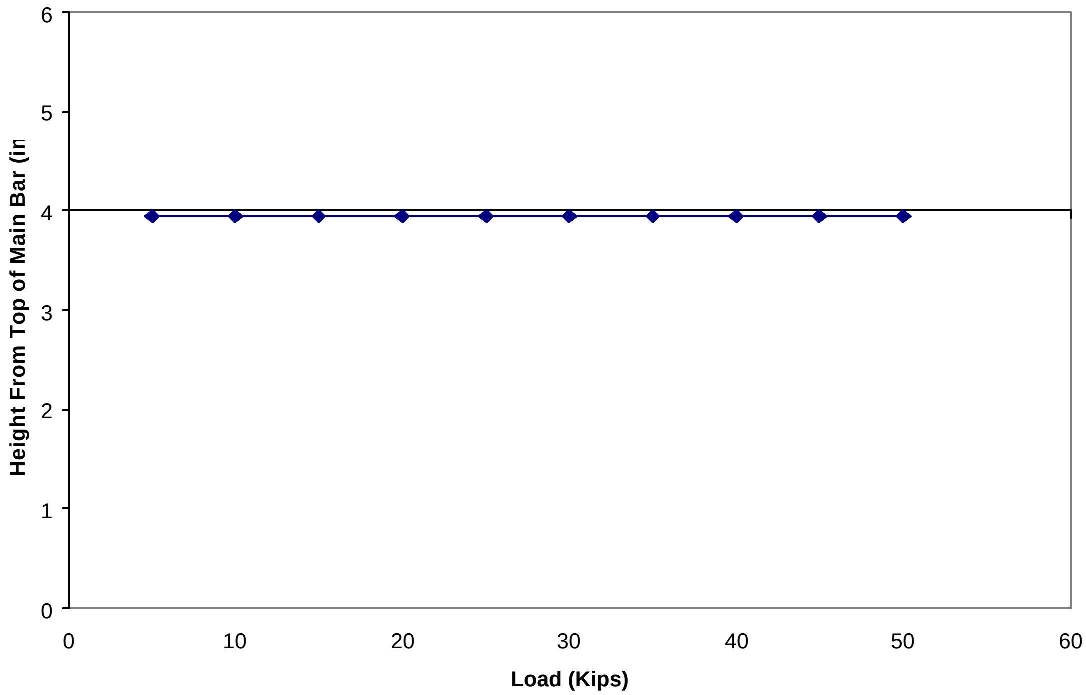

Figure B-303 Fatigue Specimen #2 Main Bar #2
- Neutral Axis Location-300K Cycles

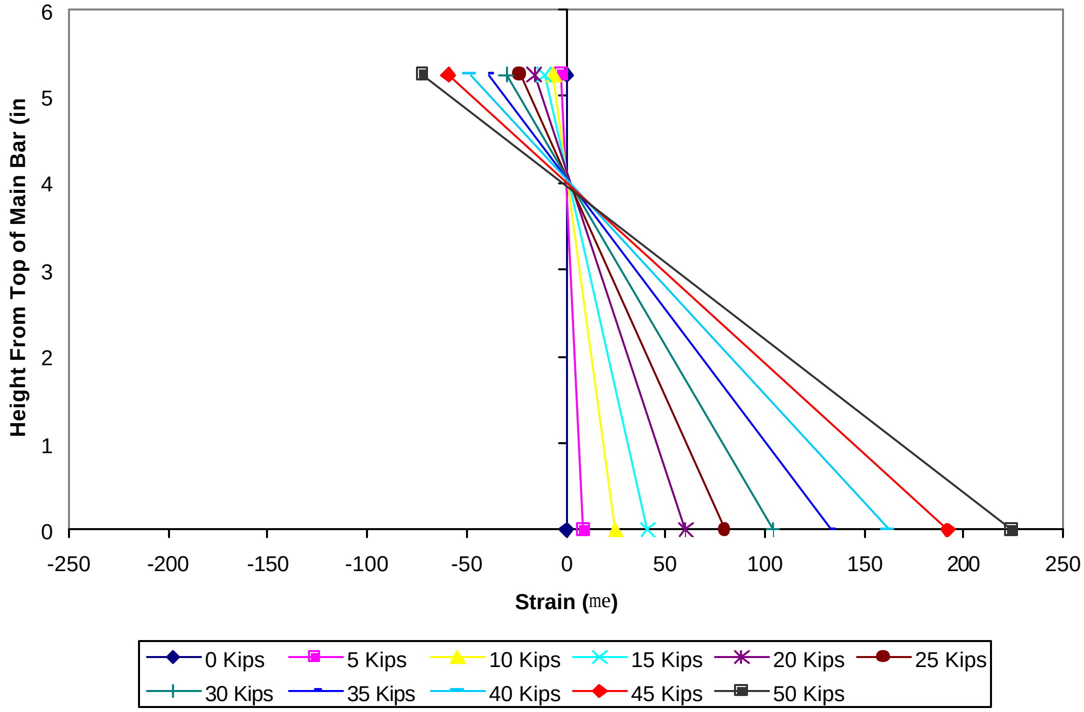

Figure B-304 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-300K Cycles

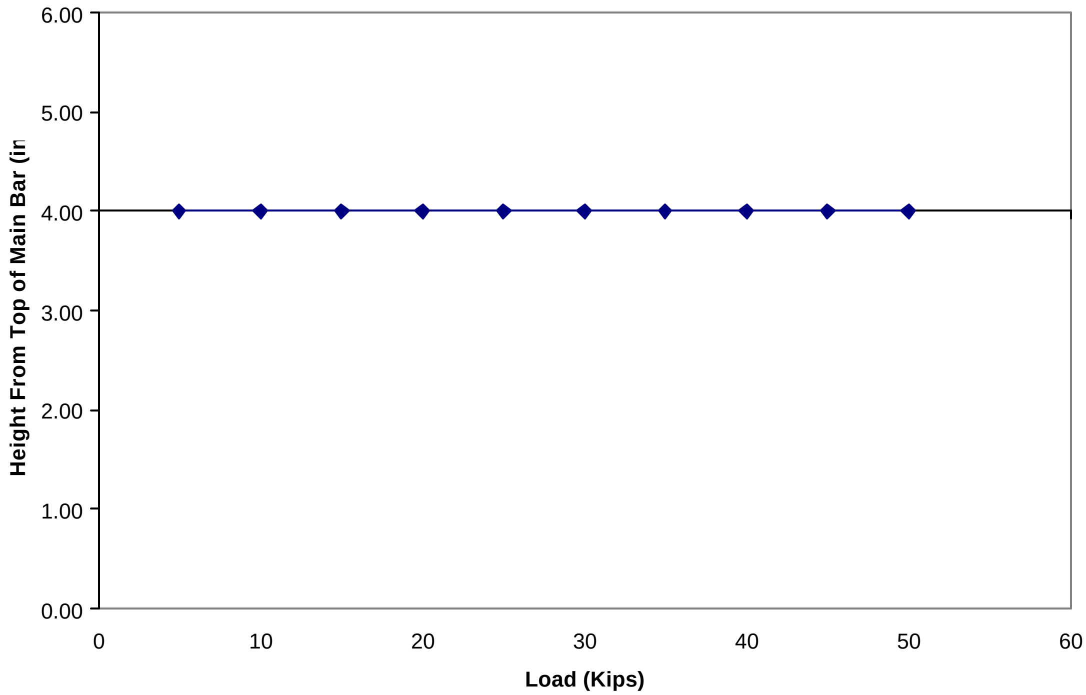

Figure B-305 Fatigue Specimen #2 Main Bar #3
- Neutral Axis Location-300K Cycles

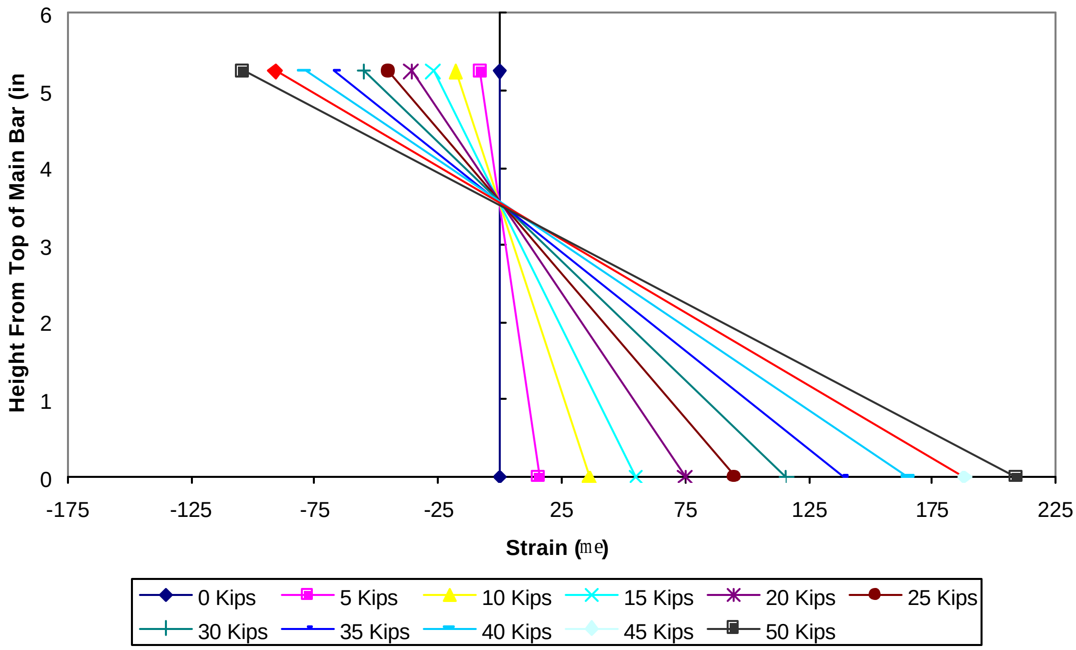

Figure B-306 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-450K Cycles

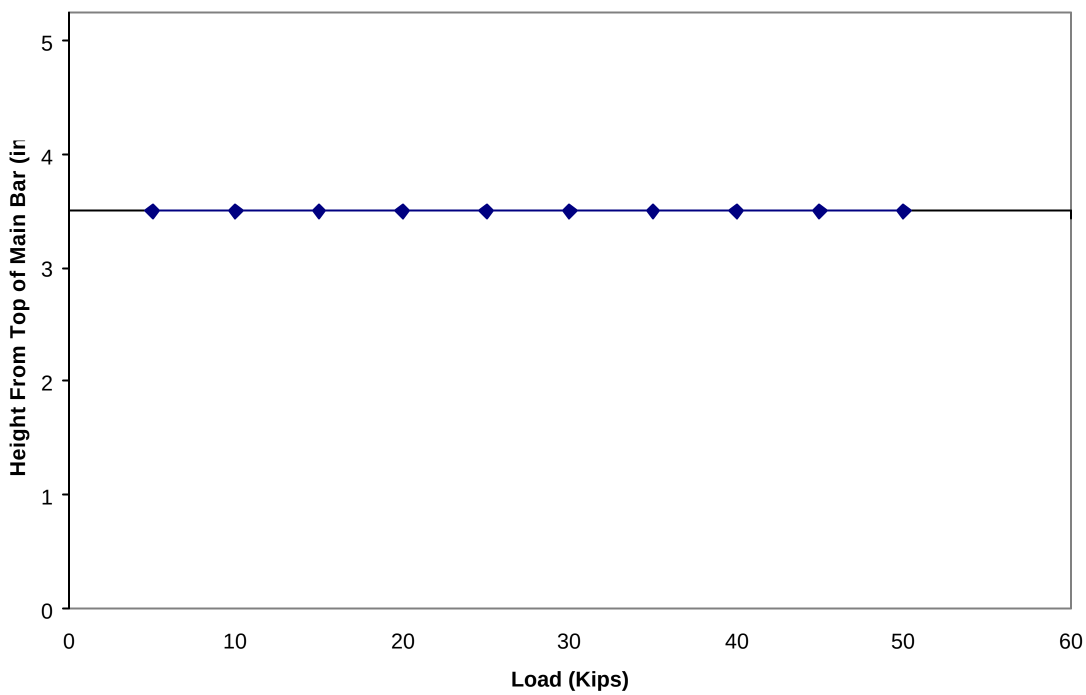

Figure B-307 Fatigue Specimen #2 Main Bar #1
- Neutral Axis Location-450K Cycles

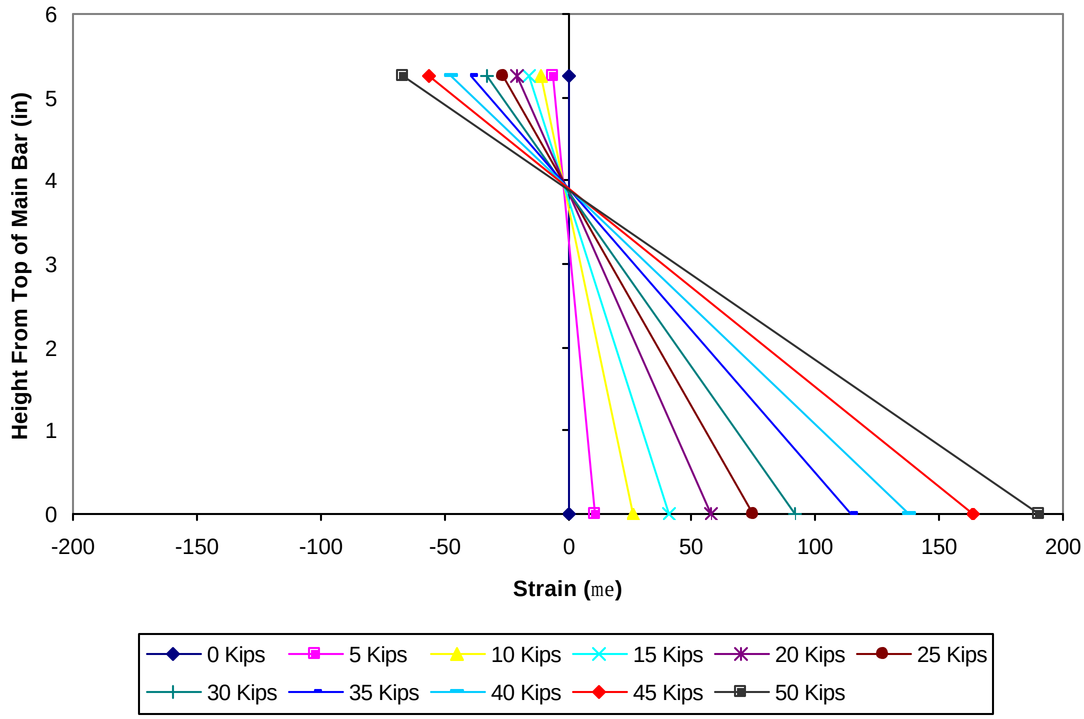

Figure B-308 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-450K Cycles

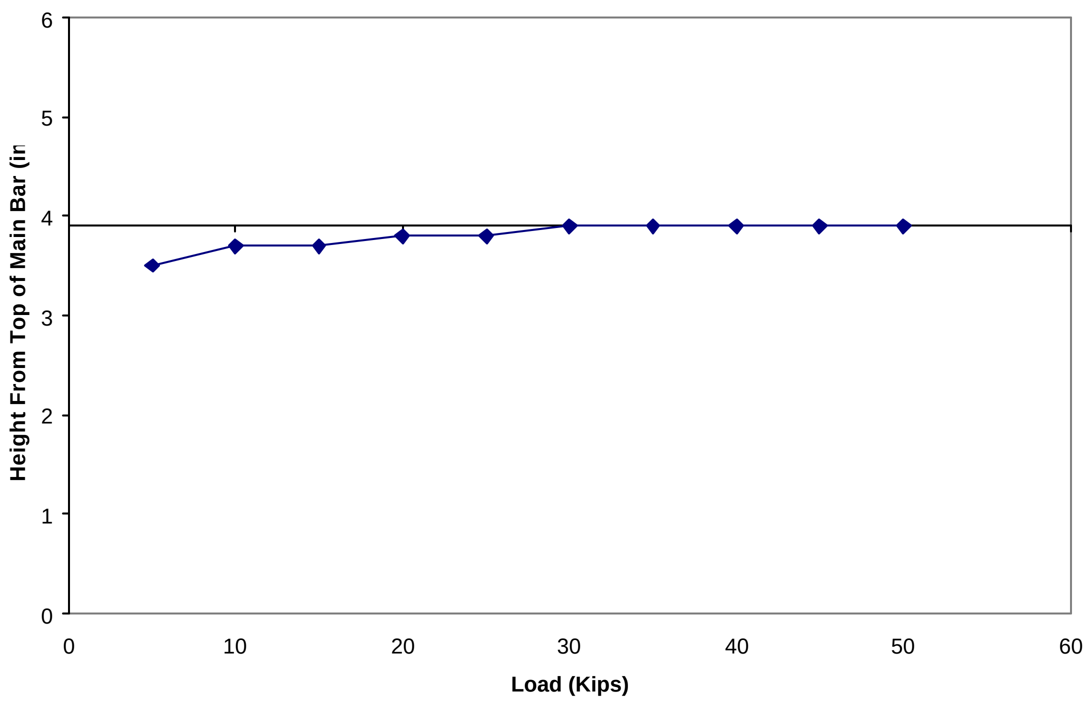

Figure B-309 Fatigue Specimen #2 Main Bar #2
- Neutral Axis Location-450K Cycles

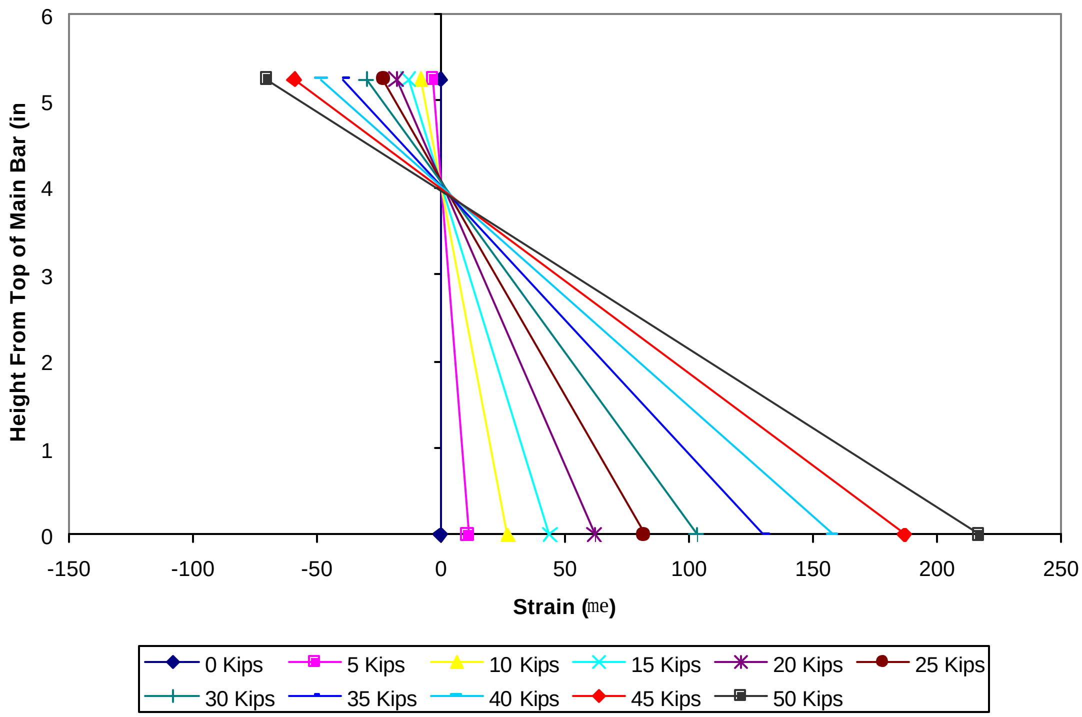

Figure B-310 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-450K Cycles

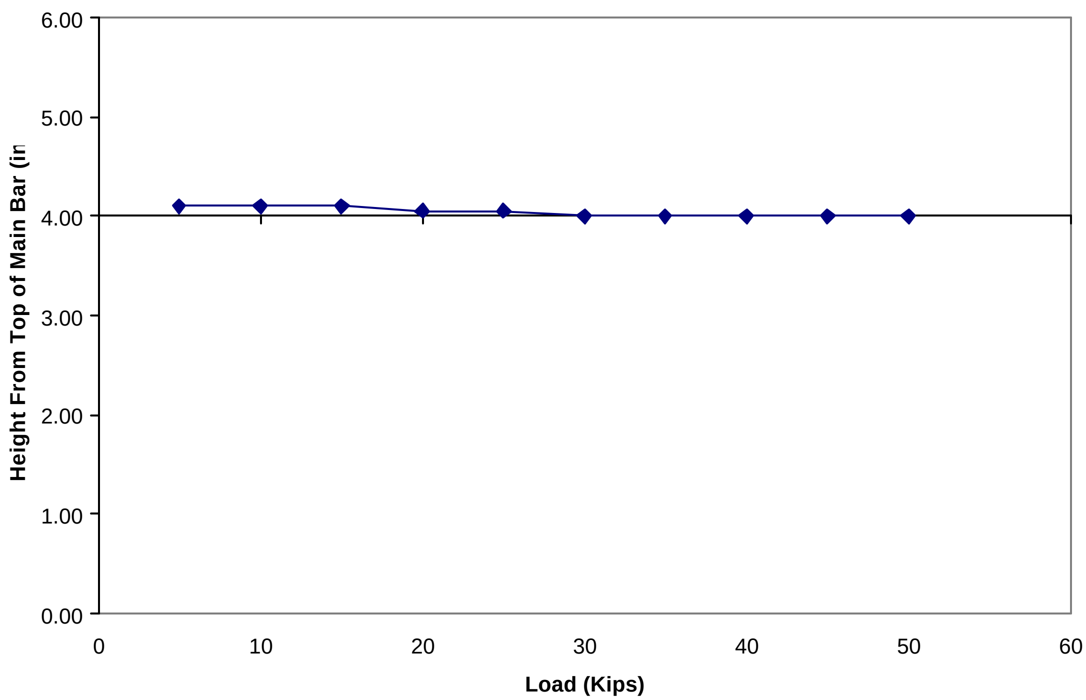

Figure B-311 Fatigue Specimen #2 Main Bar #3
- Neutral Axis Location-450K Cycles

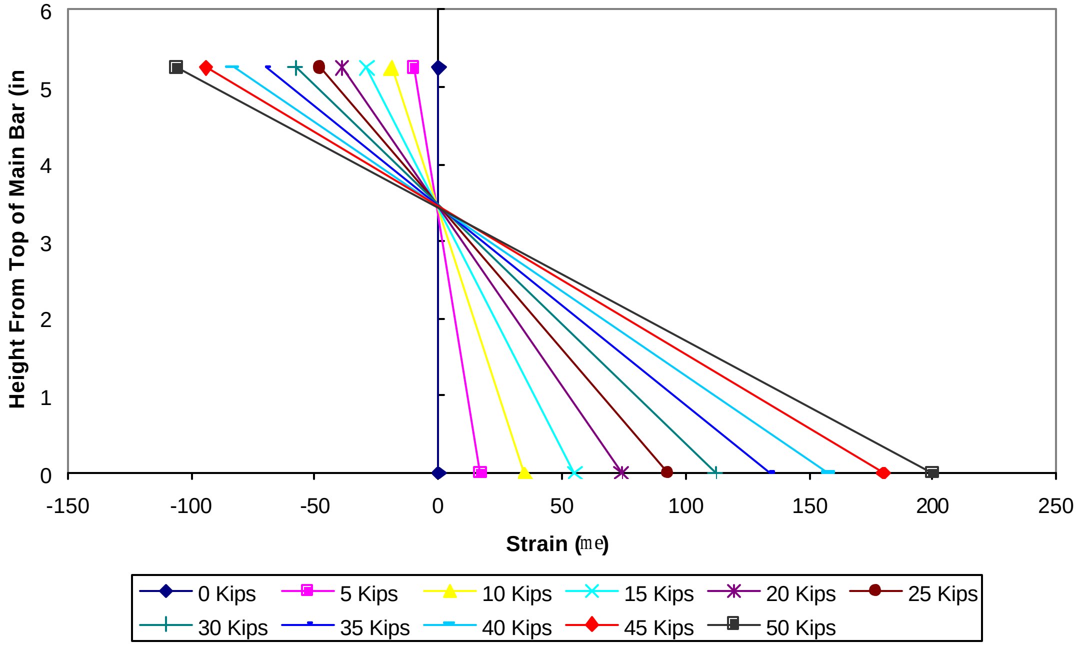

Figure B-312 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-600K Cycles

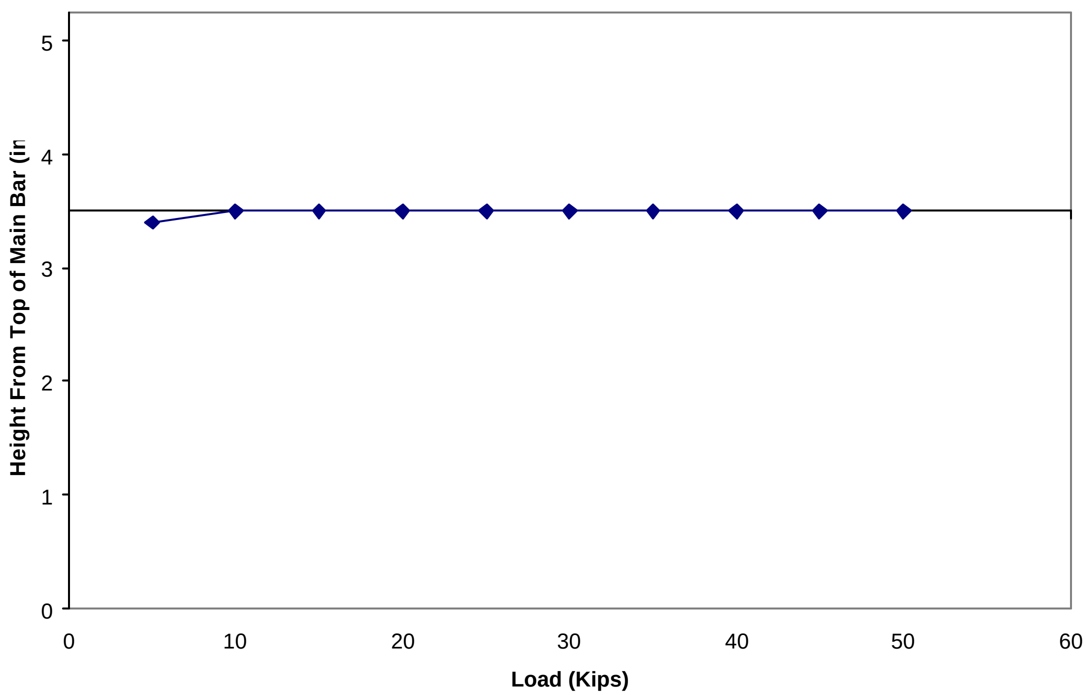

Figure B-313 Fatigue Specimen #2 Main Bar #1
- Neutral Axis Location-600K Cycles

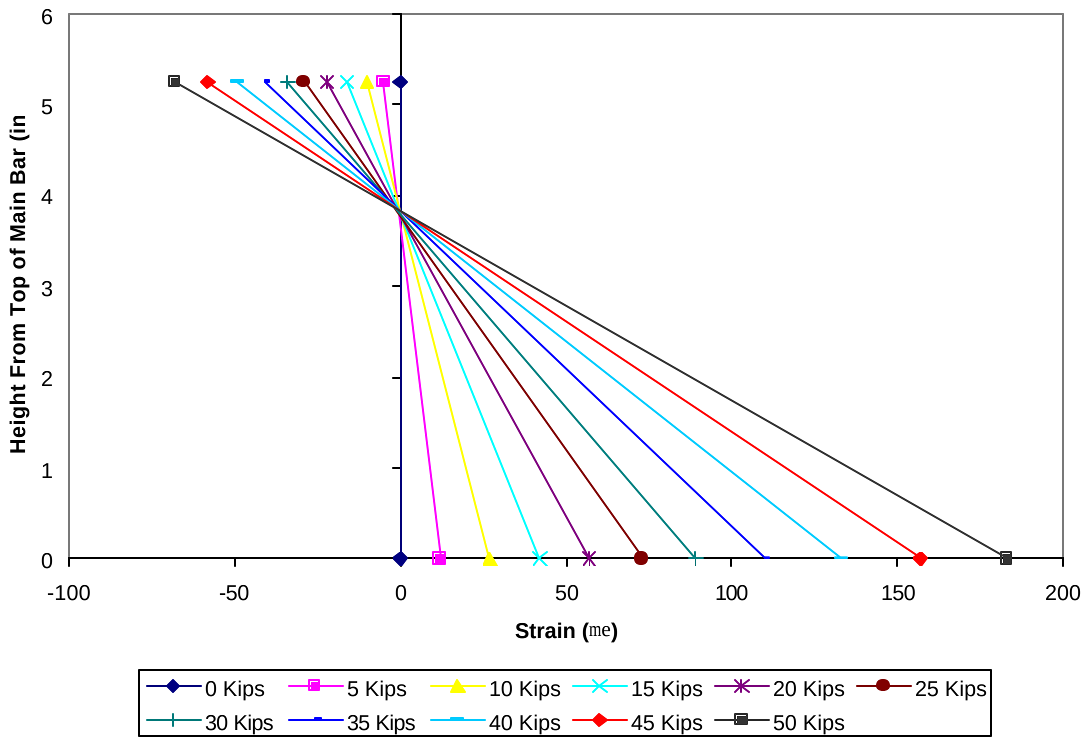

Figure B-314 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-600K Cycles

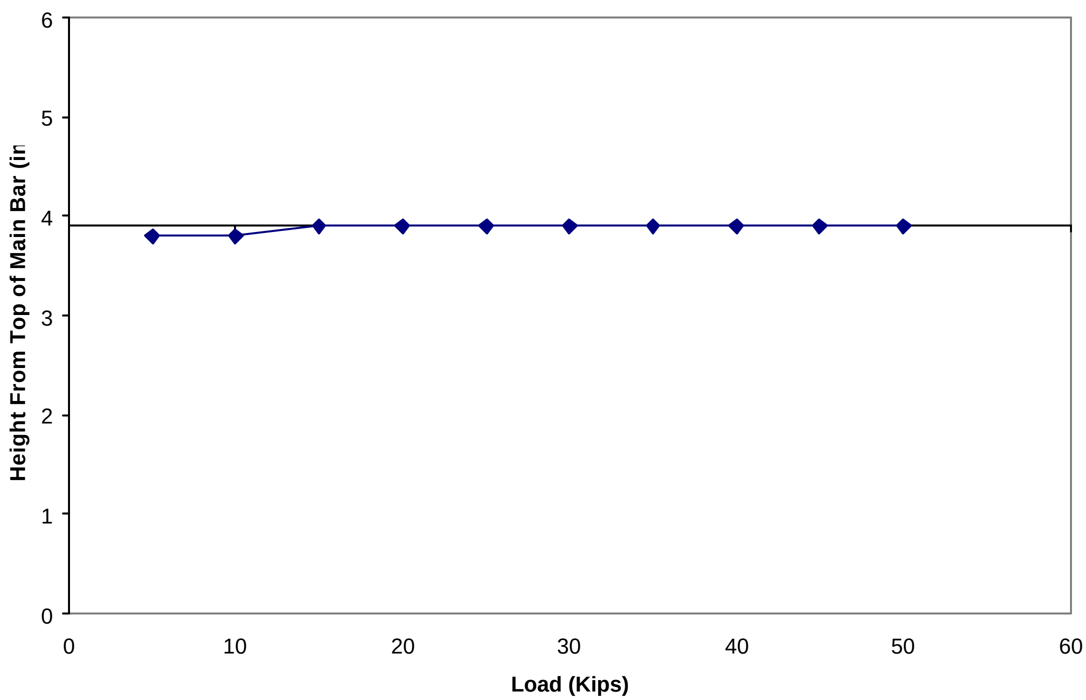

Figure B-315 Fatigue Specimen #2 Main Bar #2
- Neutral Axis Location-600K Cycles

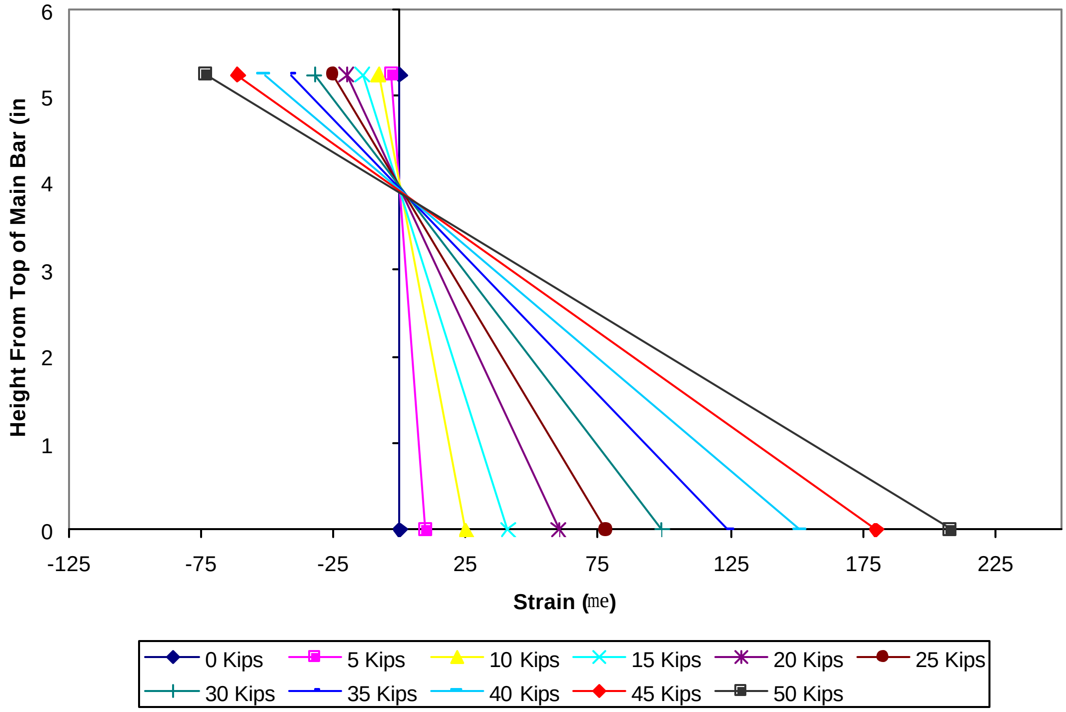

Figure B-316 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-600K Cycles

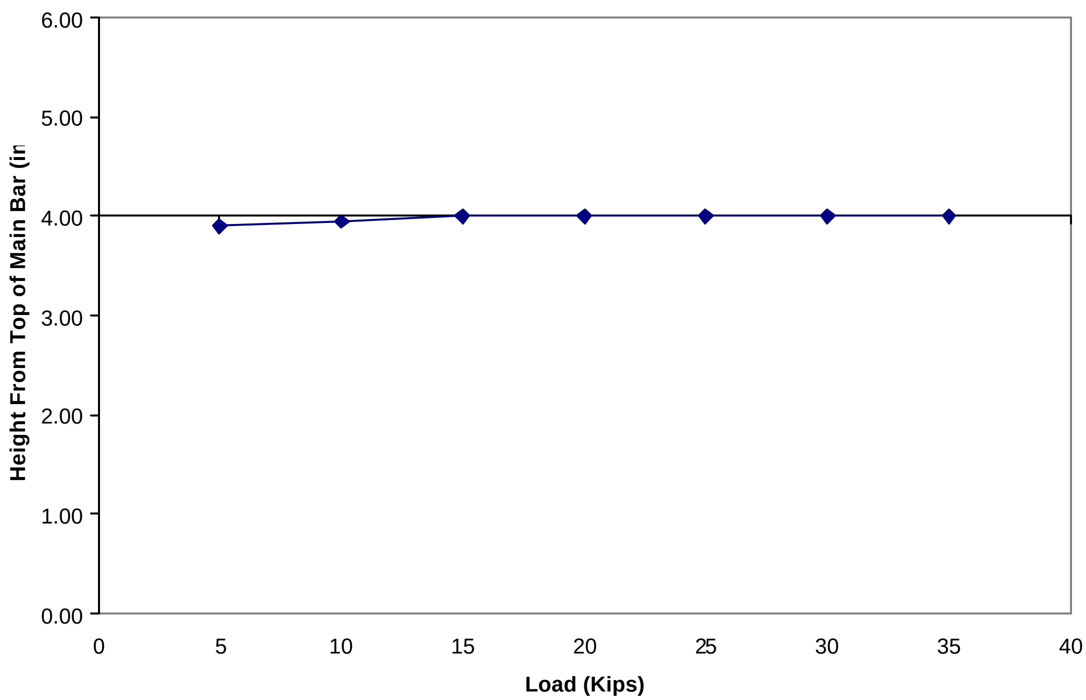

Figure B-317 Fatigue Specimen #2 Main Bar #3
- Neutral Axis Location-600K Cycles

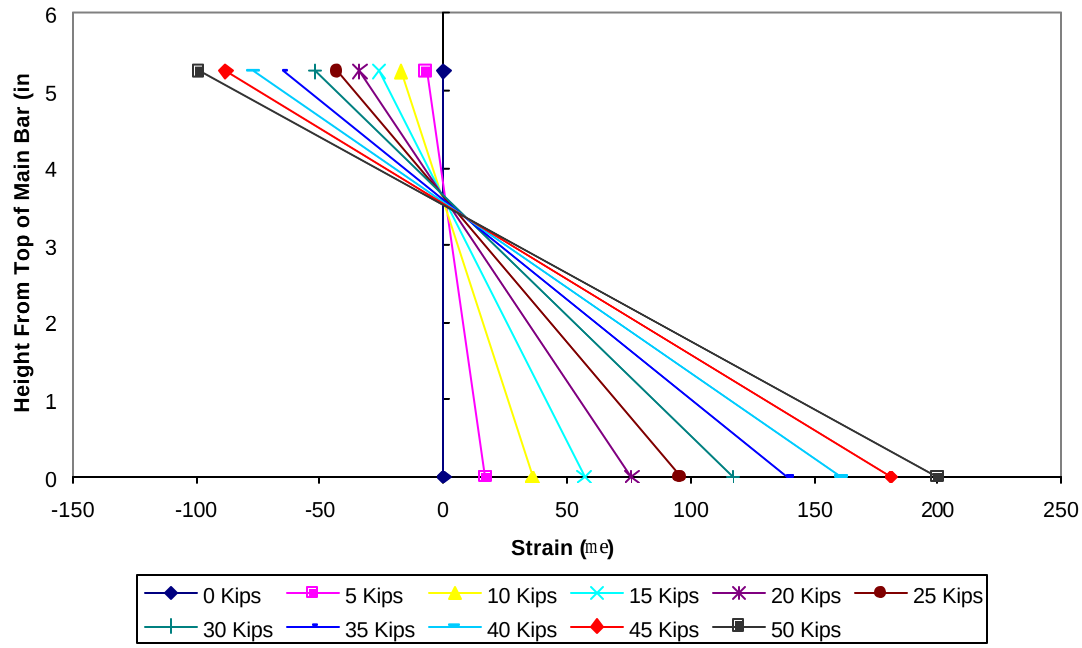

Figure B-318 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-750K Cycles

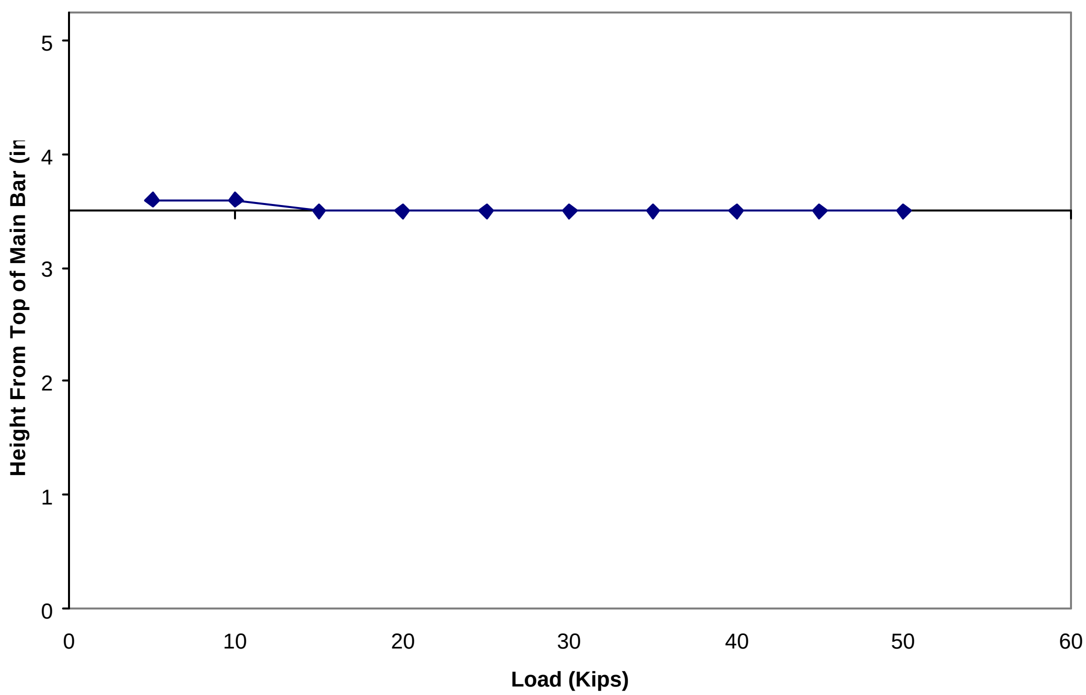

Figure B-319 Fatigue Specimen #2 Main Bar #1
- Neutral Axis Location-750K Cycles

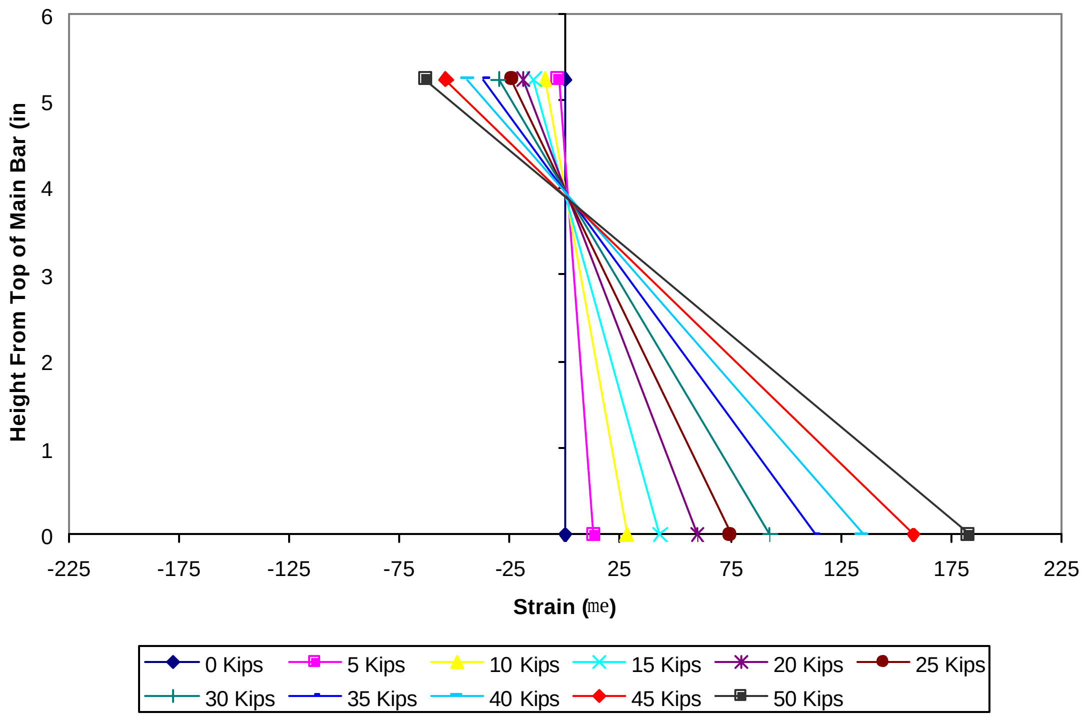

Figure B-320 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-750K Cycles

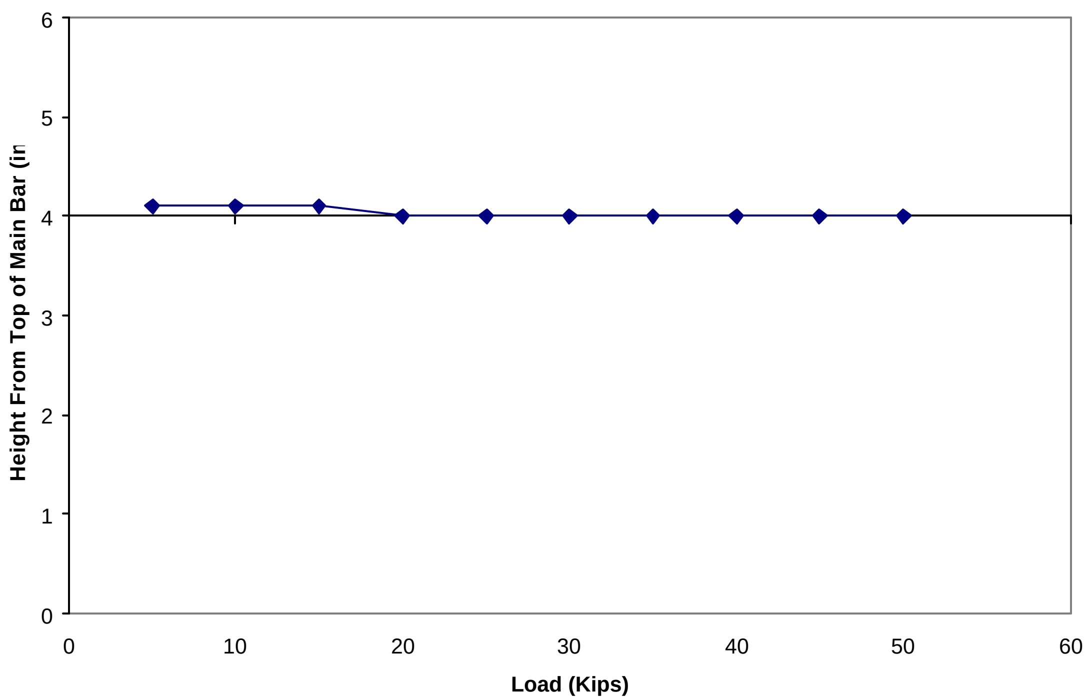

Figure B-321 Fatigue Specimen #2 Main Bar #2
- Neutral Axis Location-750K Cycles

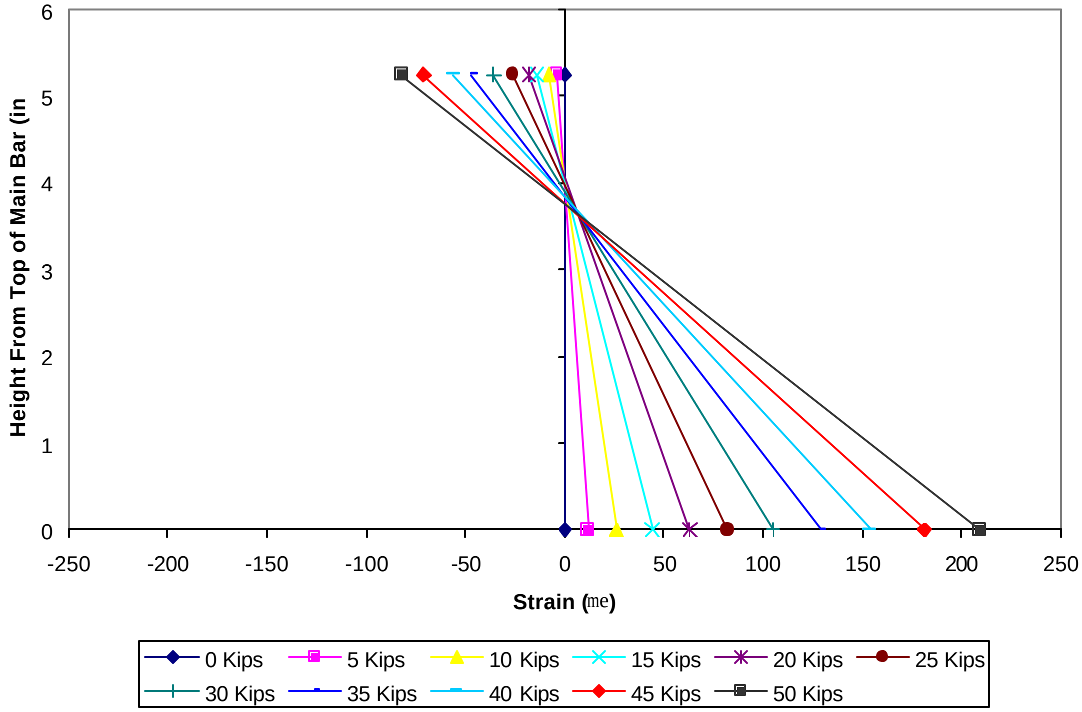

Figure B-322 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-750K Cycles

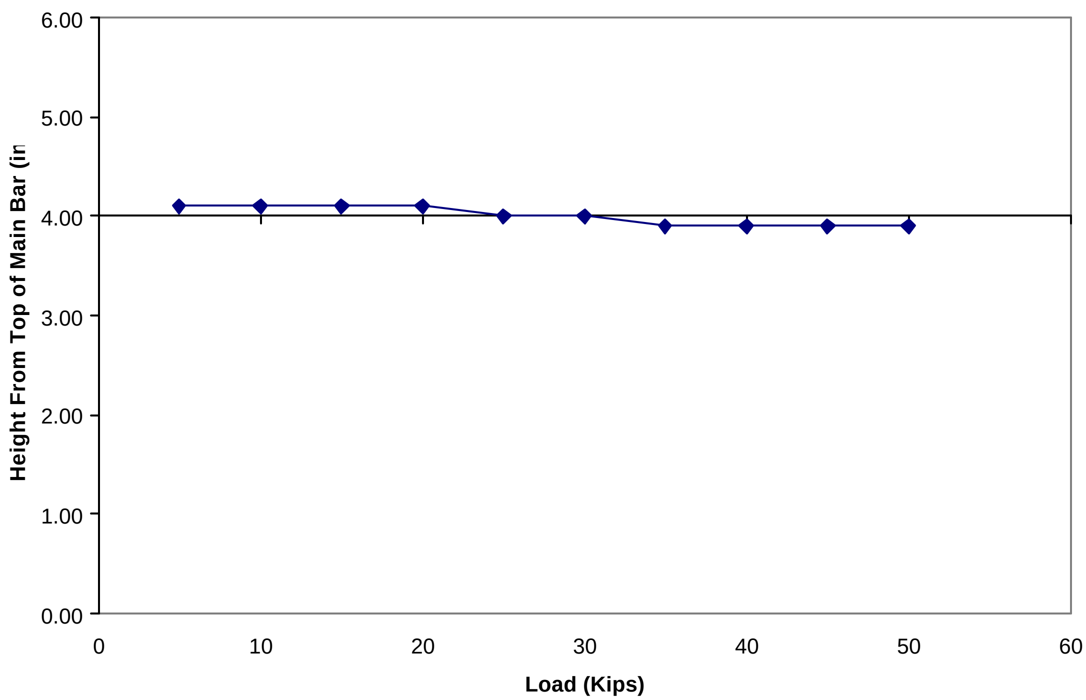

Figure B-323 Fatigue Specimen #2 Main Bar #3
- Neutral Axis Location-750K Cycles

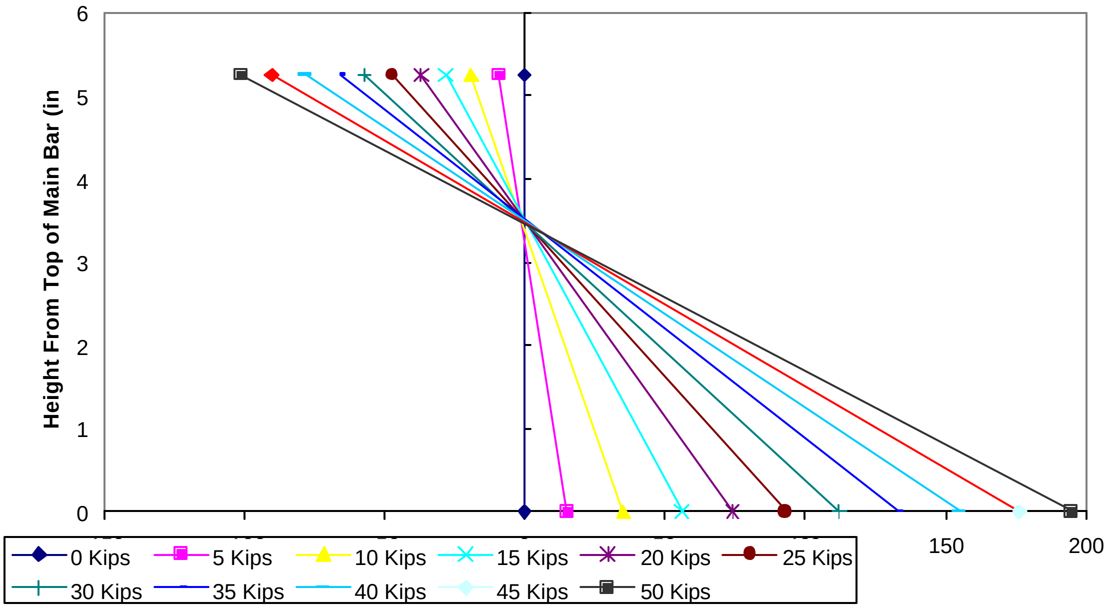

Figure B-324 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-900K Cycles

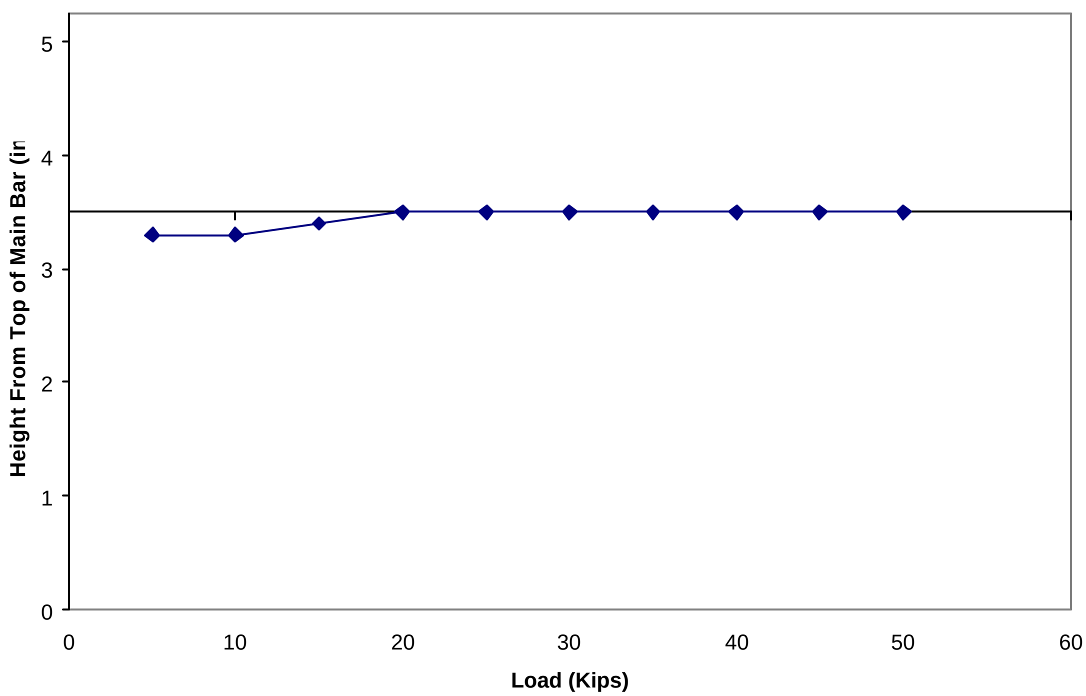

Figure B-325 Fatigue Specimen #2 Main Bar #1
- Neutral Axis Location-900K Cycles

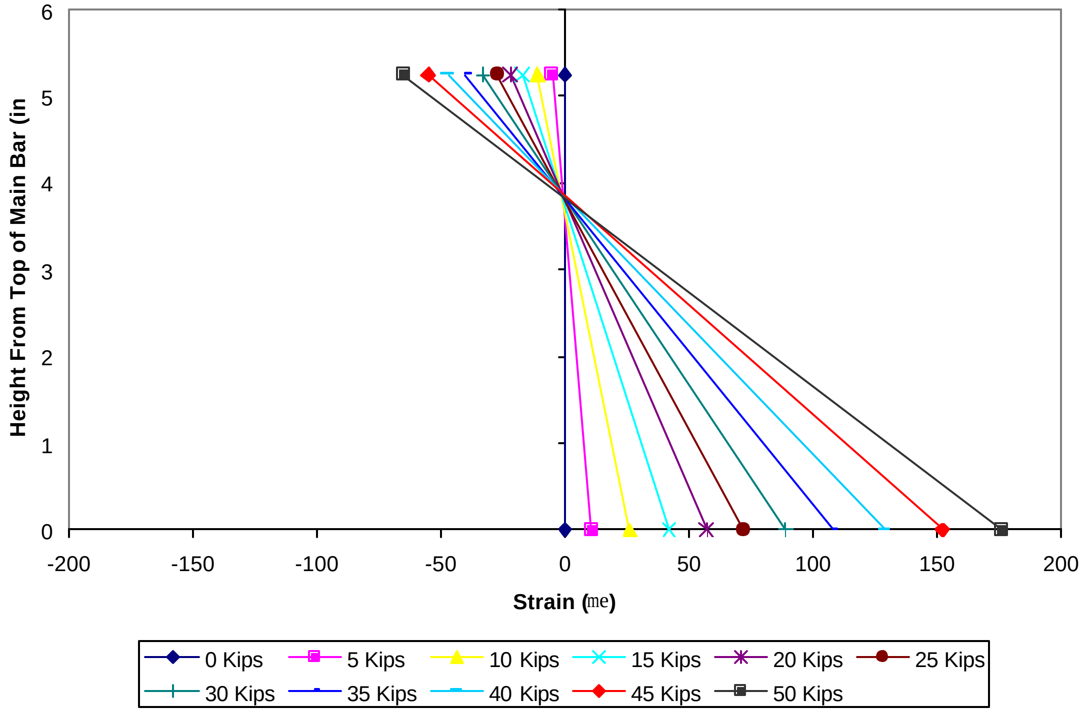

Figure B-326 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-900K Cycles

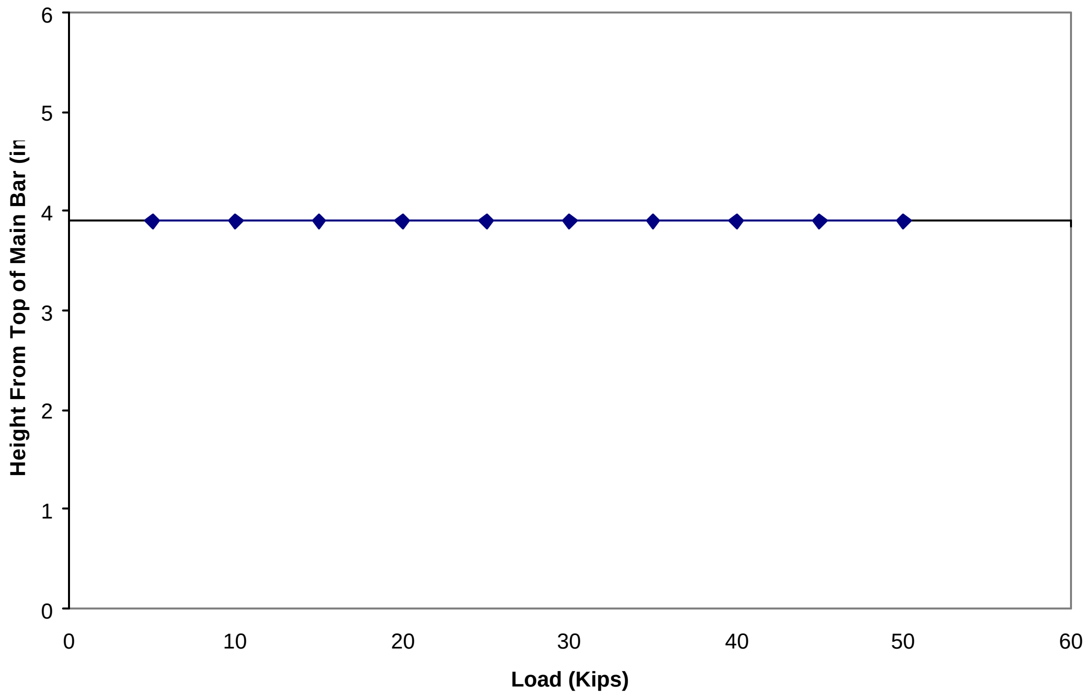

Figure B-327 Fatigue Specimen #2 Main Bar #2
- Neutral Axis Location-900K Cycles

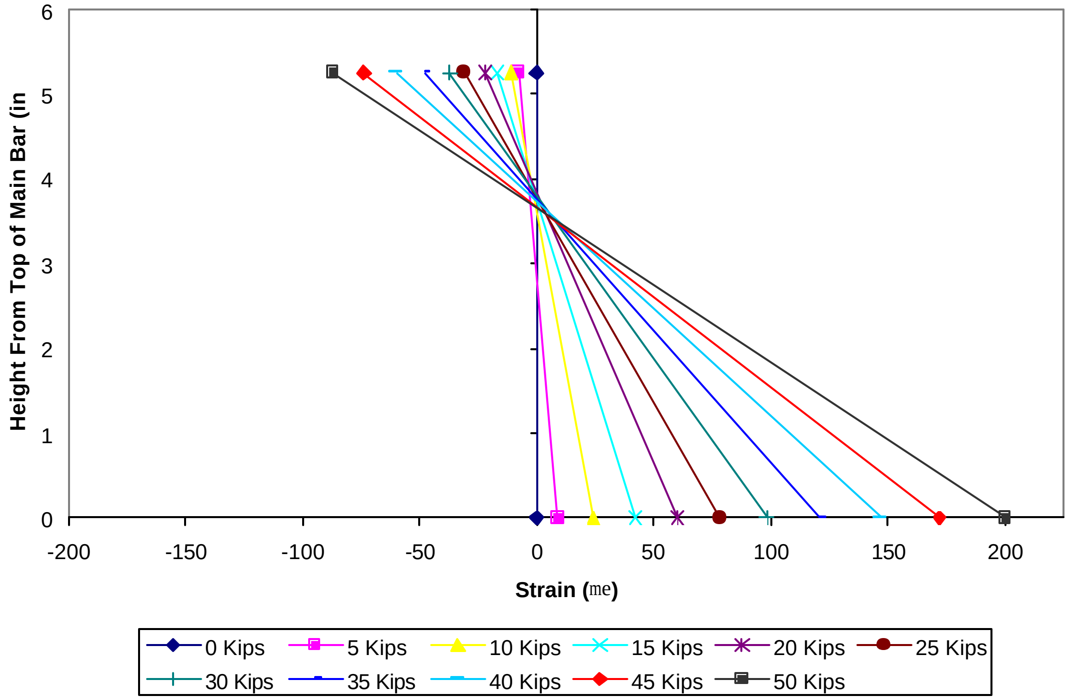

Figure B-328 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-900K Cycles

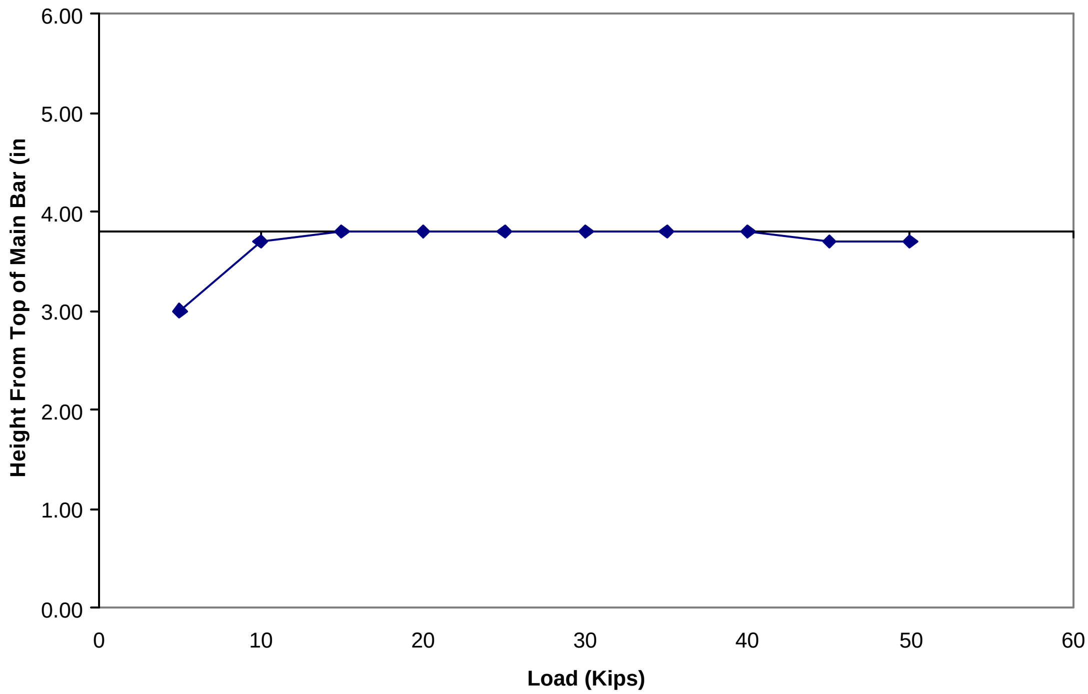

Figure B-329 Fatigue Specimen #2 Main Bar #3
- Neutral Axis Location-900K Cycles

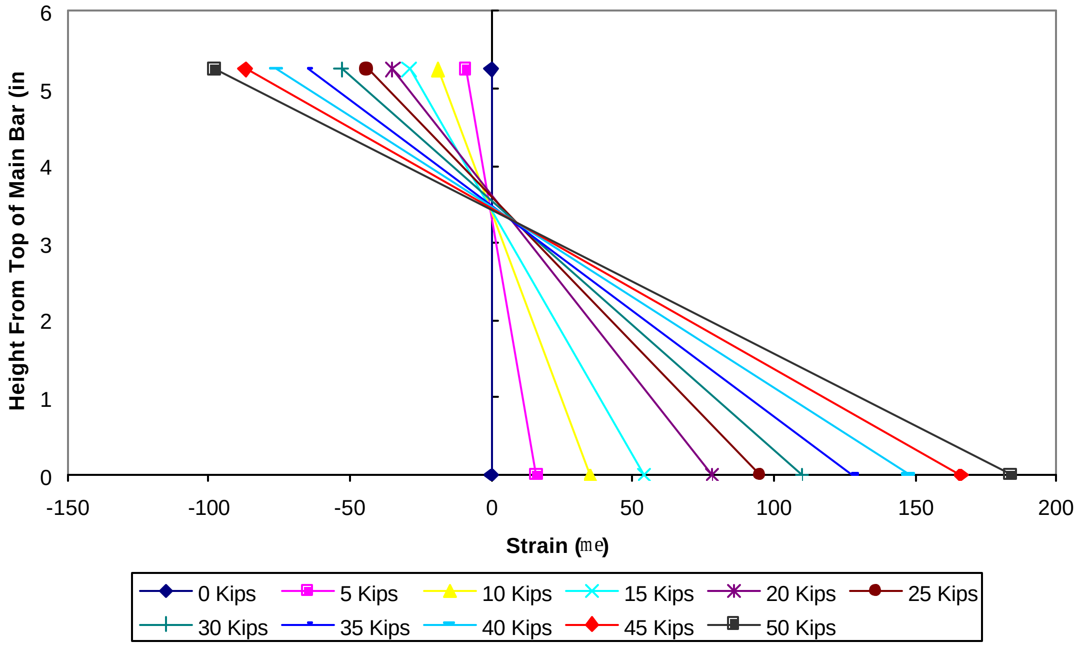

Figure B-330 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-1050K Cycles

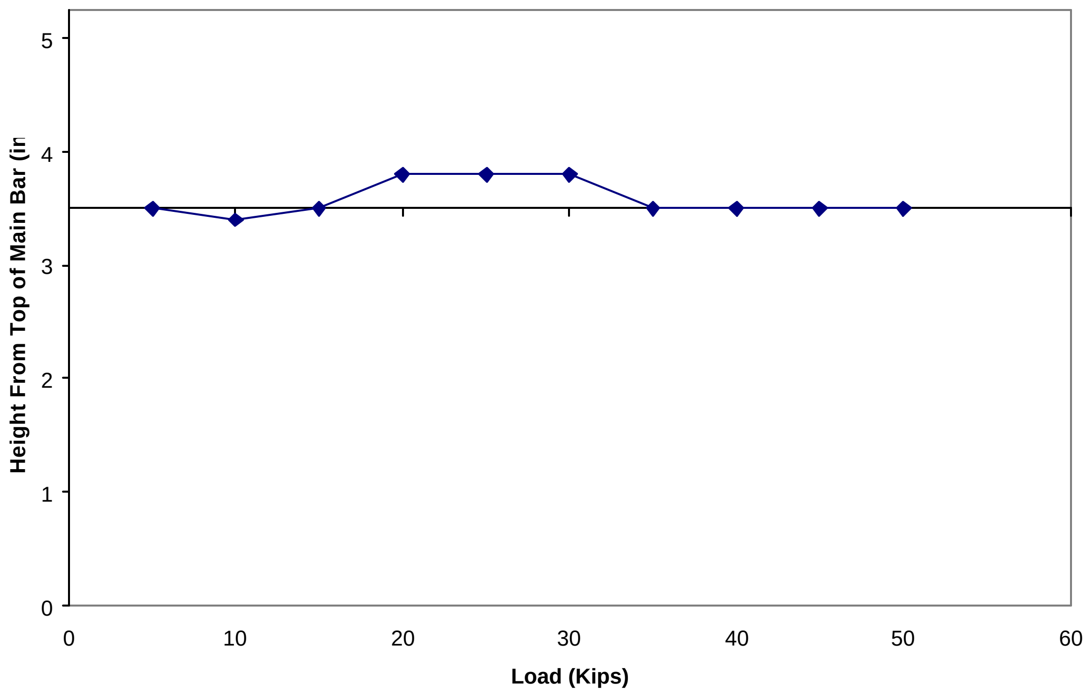

Figure B-331 Fatigue Specimen #2 Main Bar #1
-Neutral Axis Location-1050K Cycles

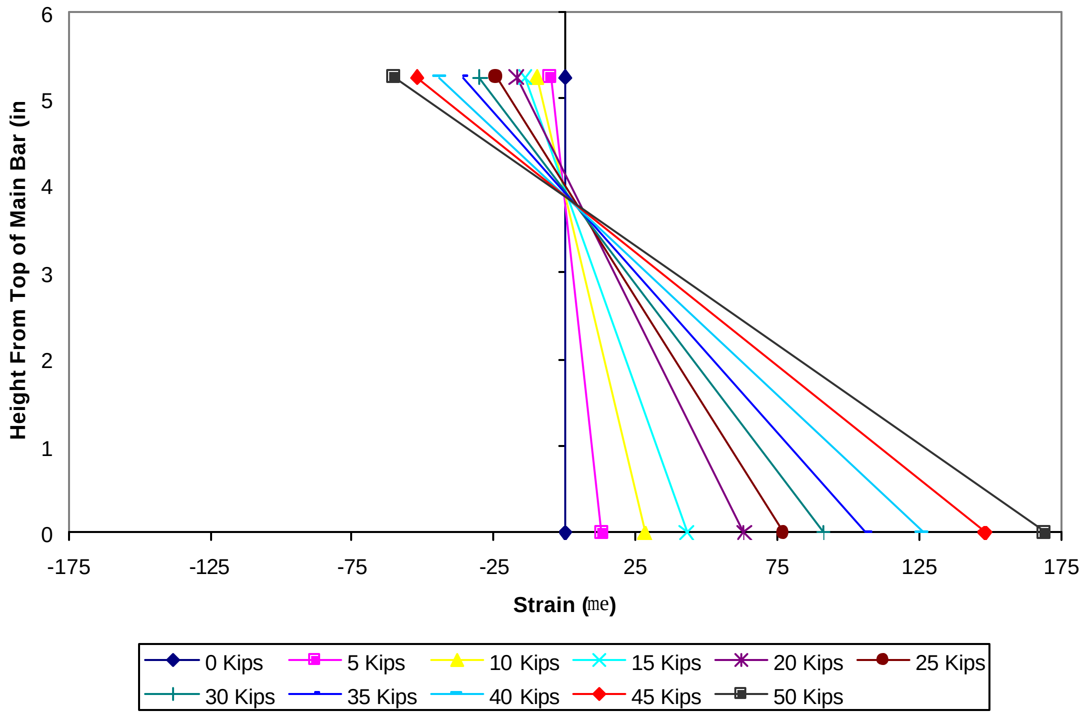

Figure B-332 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-1050K Cycles

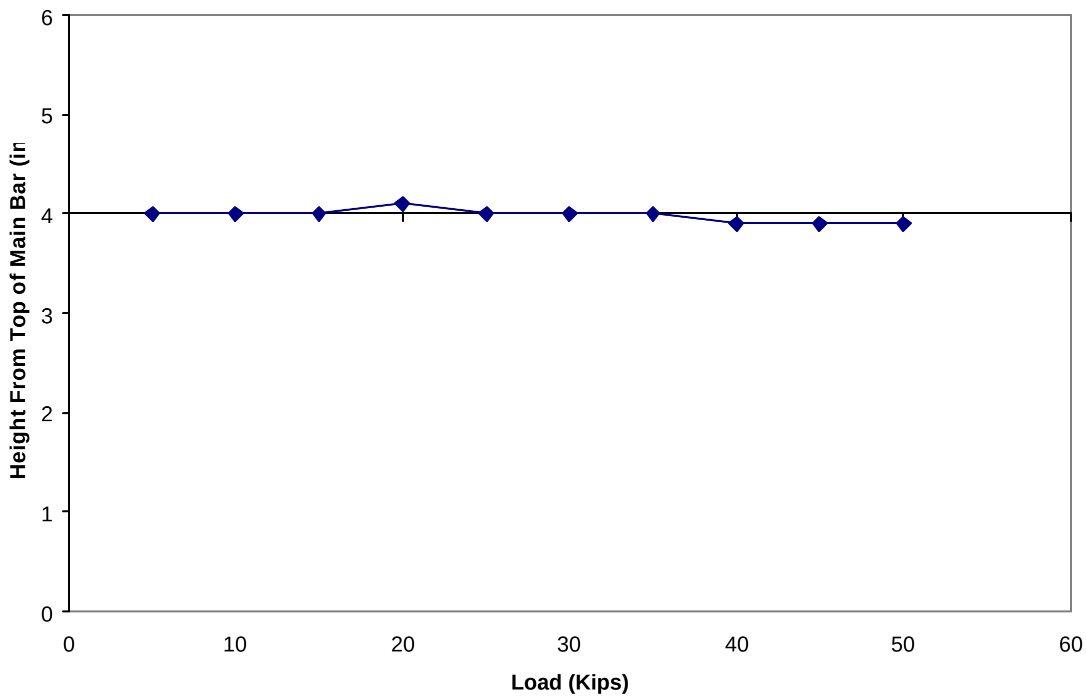

Figure B-333 Fatigue Specimen #2 Main Bar #2
-Neutral Axis Location-1050K Cycles

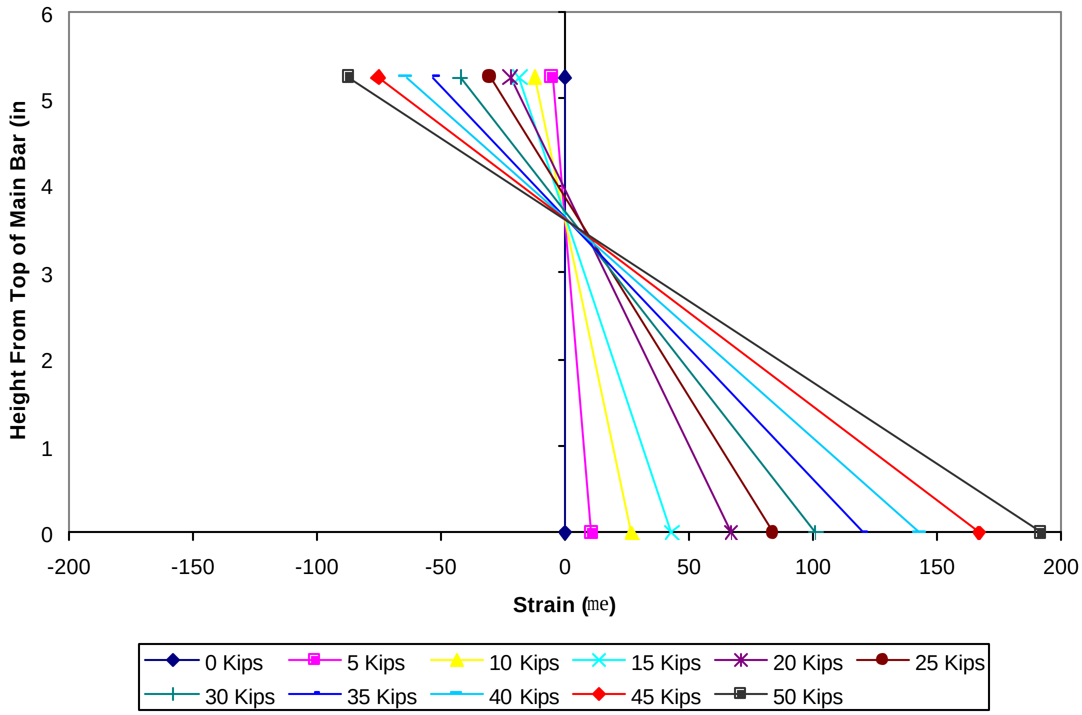

Figure B-334 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-1050K Cycles

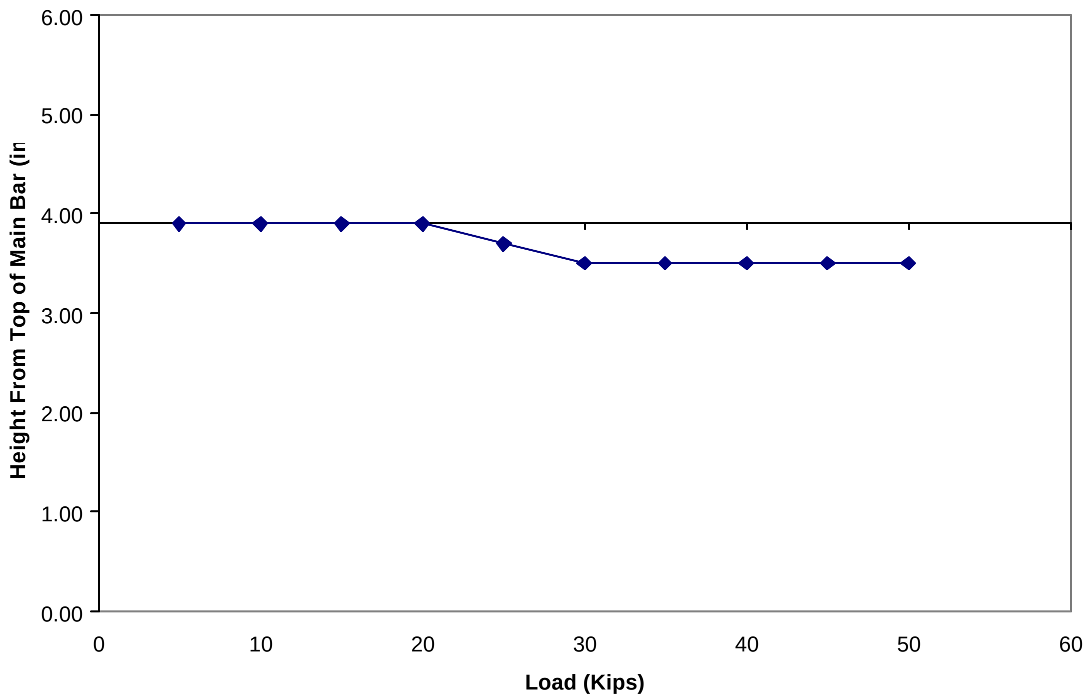

Figure B-335 Fatigue Specimen #2 Main Bar #3
-Neutral Axis Location-1050K Cycles

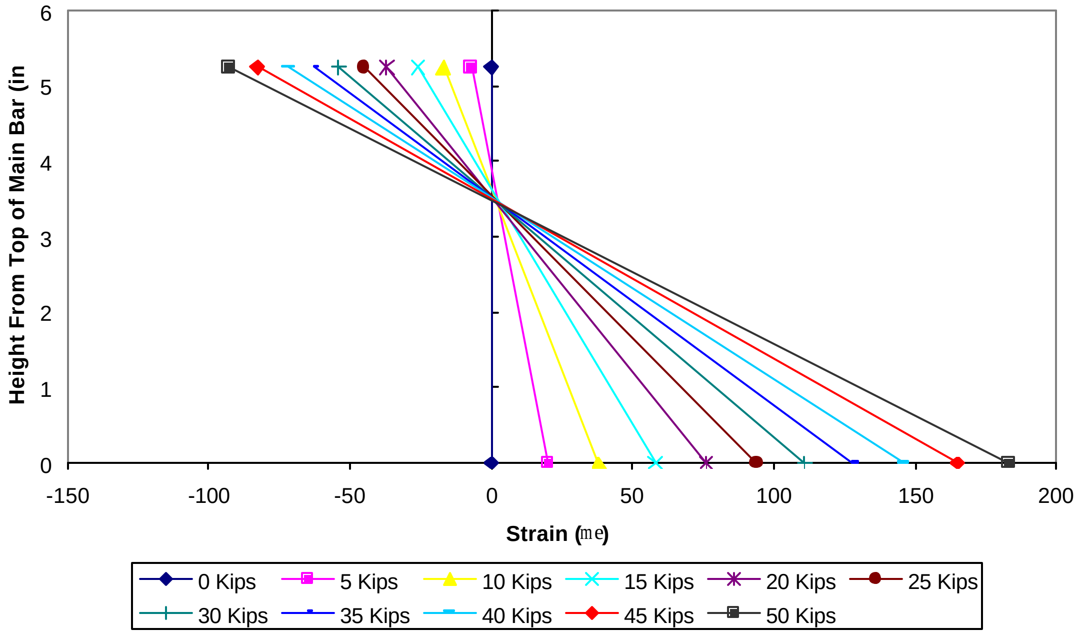

Figure B-336 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-1200K Cycles

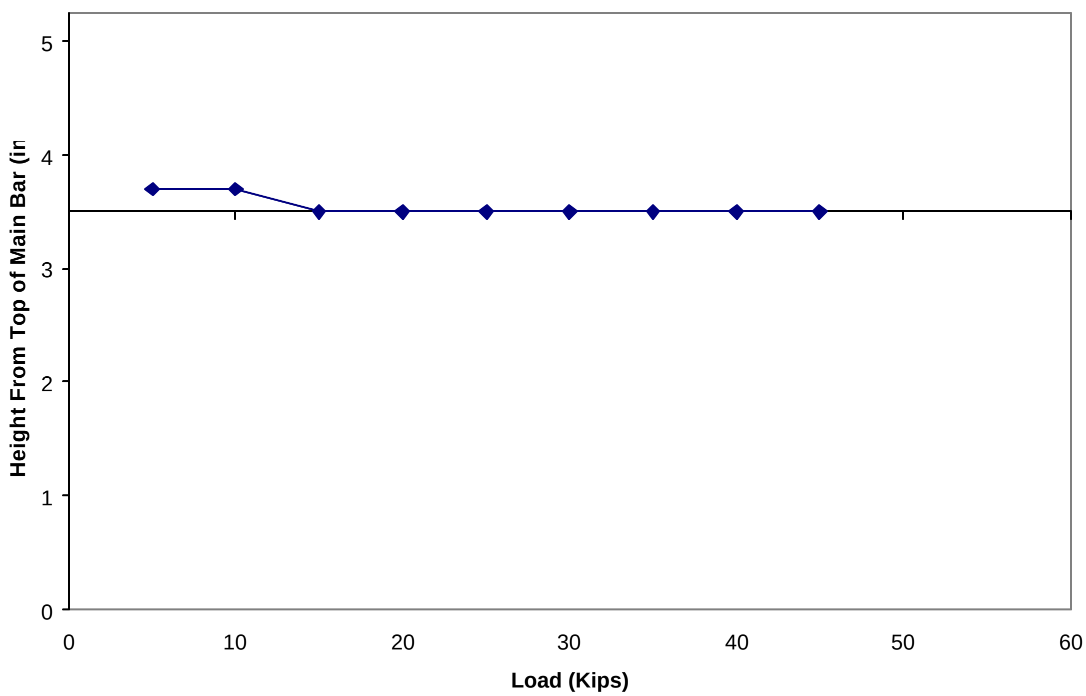

Figure B-337 Fatigue Specimen #2 Main Bar #1
-Neutral Axis Location-1200K Cycles

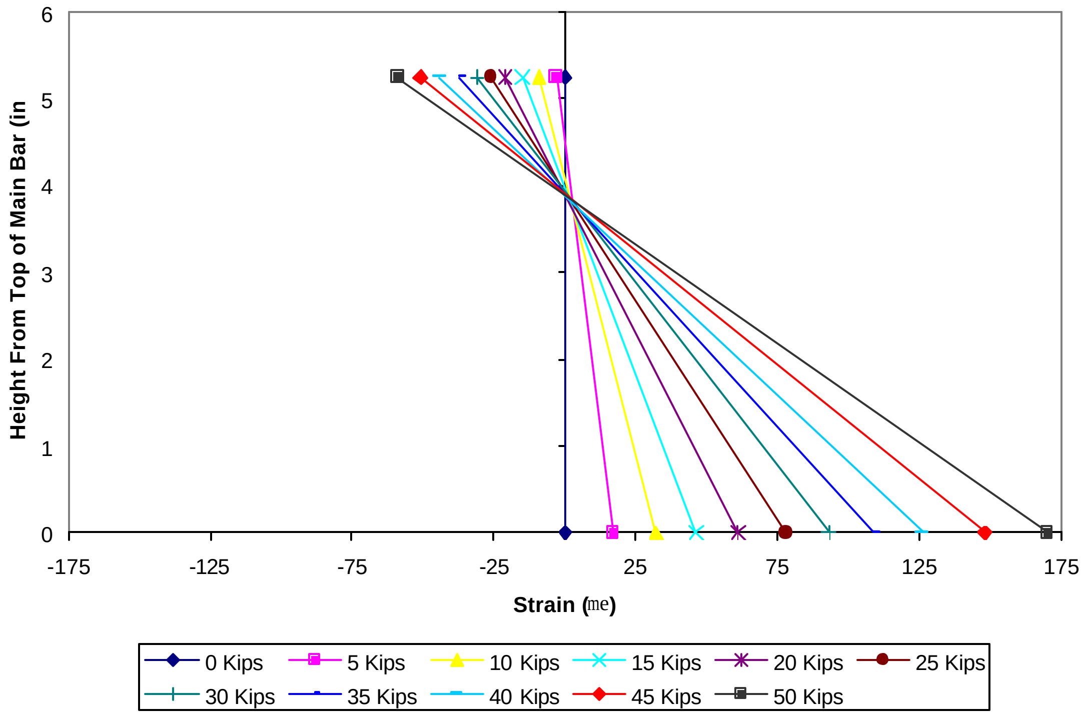

Figure B-338 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-1200K Cycles

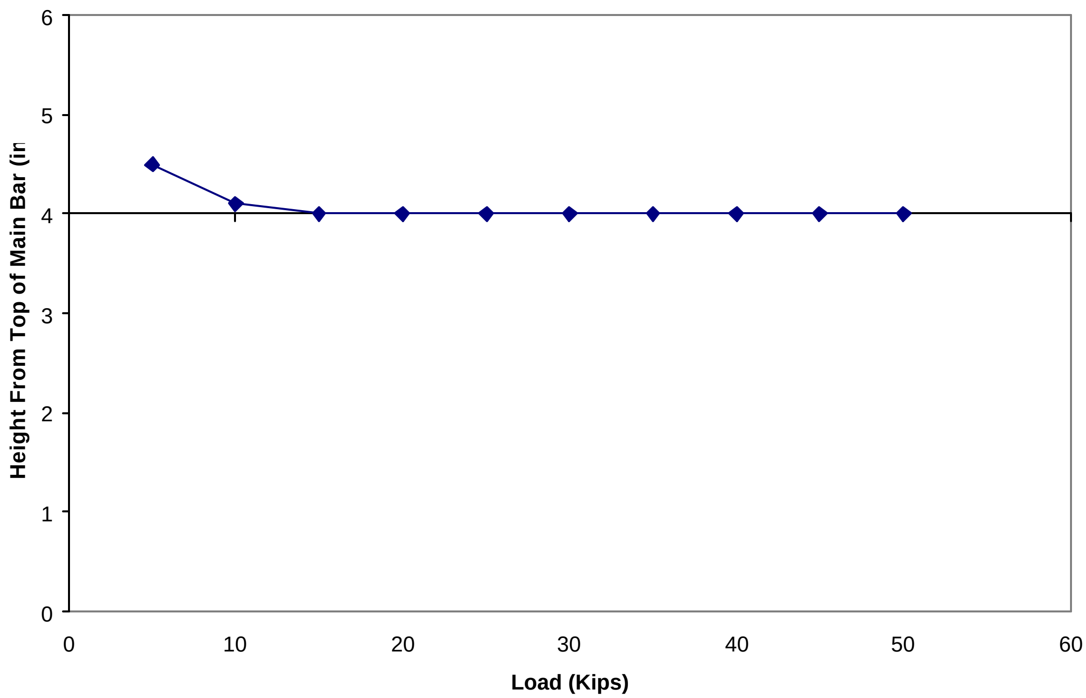

Figure B-339 Fatigue Specimen #2 Main Bar #2
-Neutral Axis Location-1200K Cycles

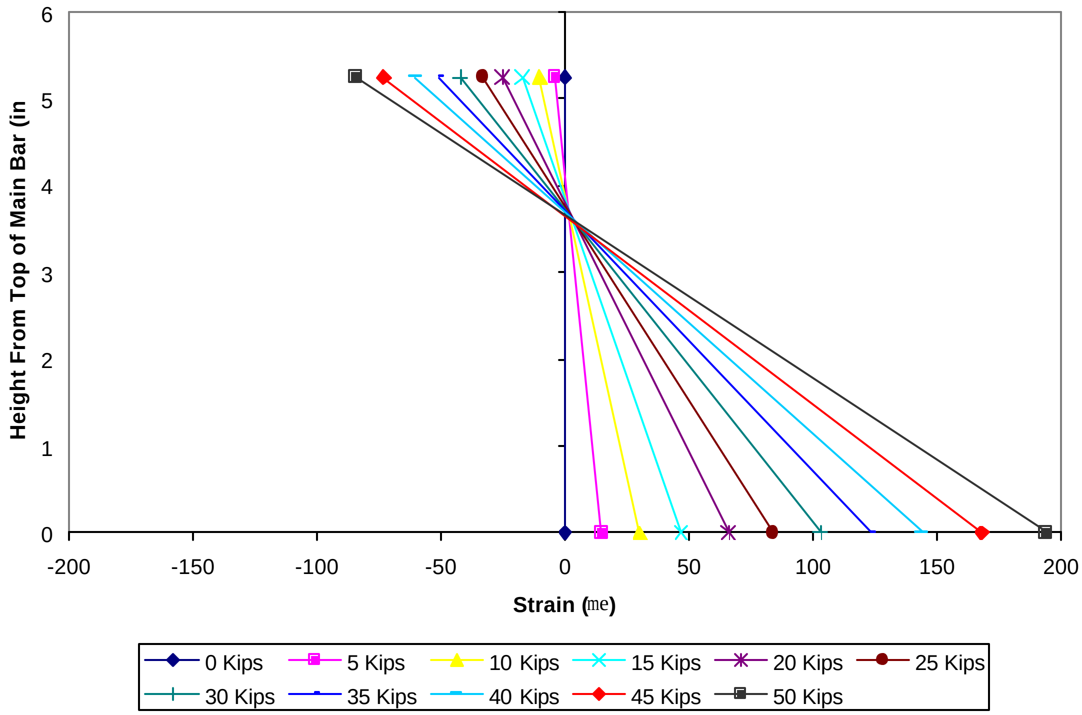

Figure B-340 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-1200K Cycles

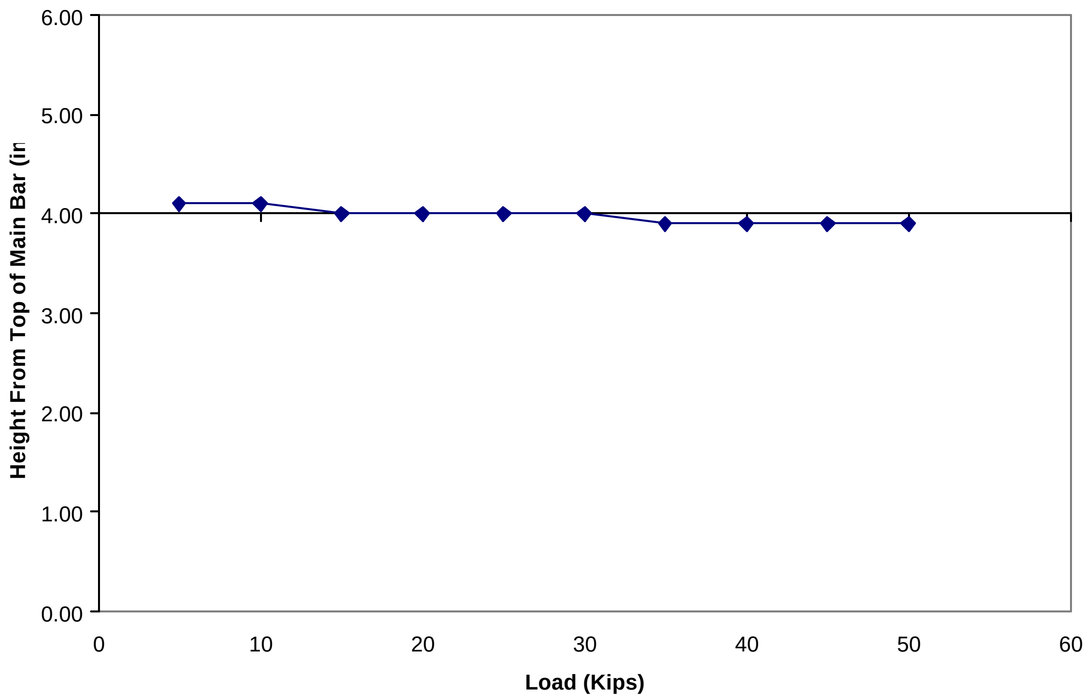

Figure B-341 Fatigue Specimen #2 Main Bar #3
-Neutral Axis Location-1200K Cycles

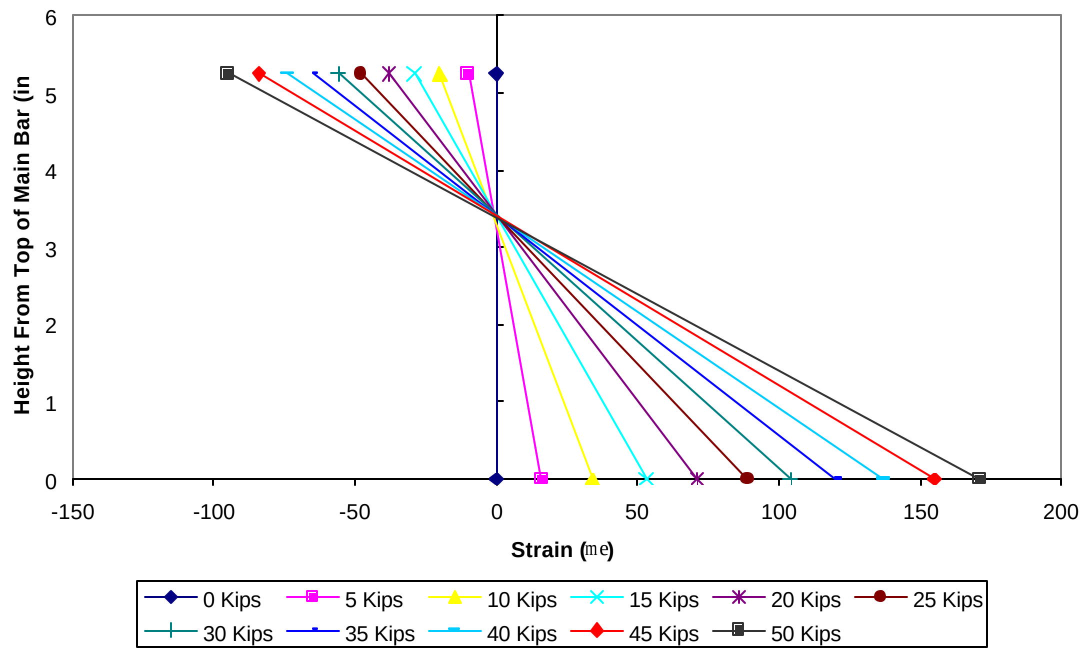

Figure B-342 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-1350K Cycles

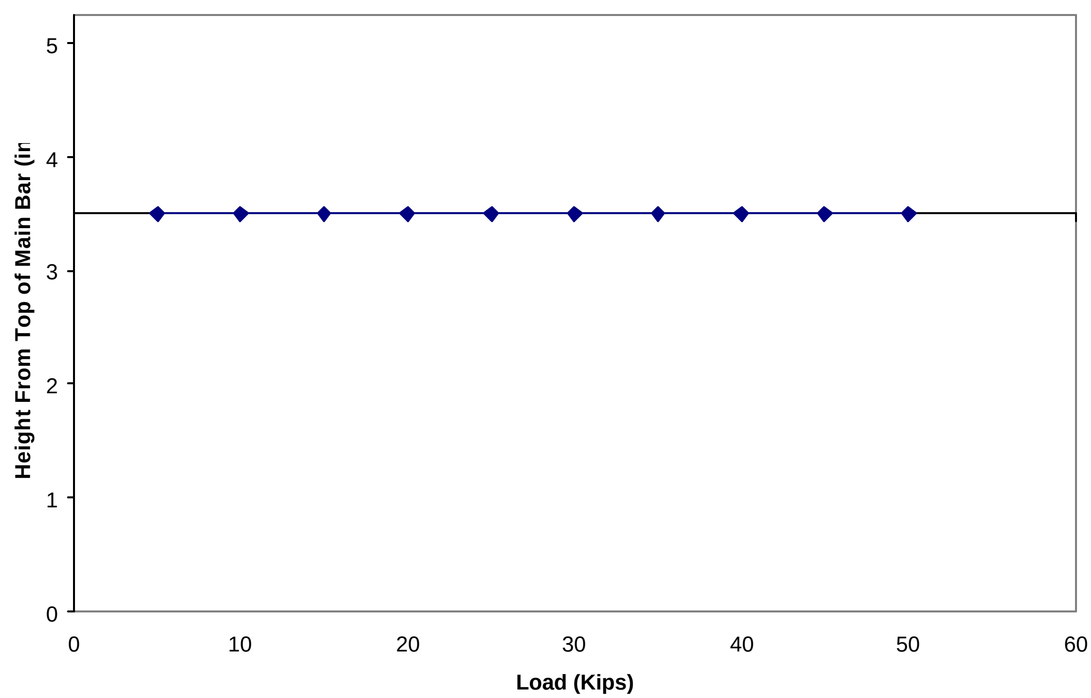

Figure B-343 Fatigue Specimen #2 Main Bar #1
-Neutral Axis Location-1350K Cycles

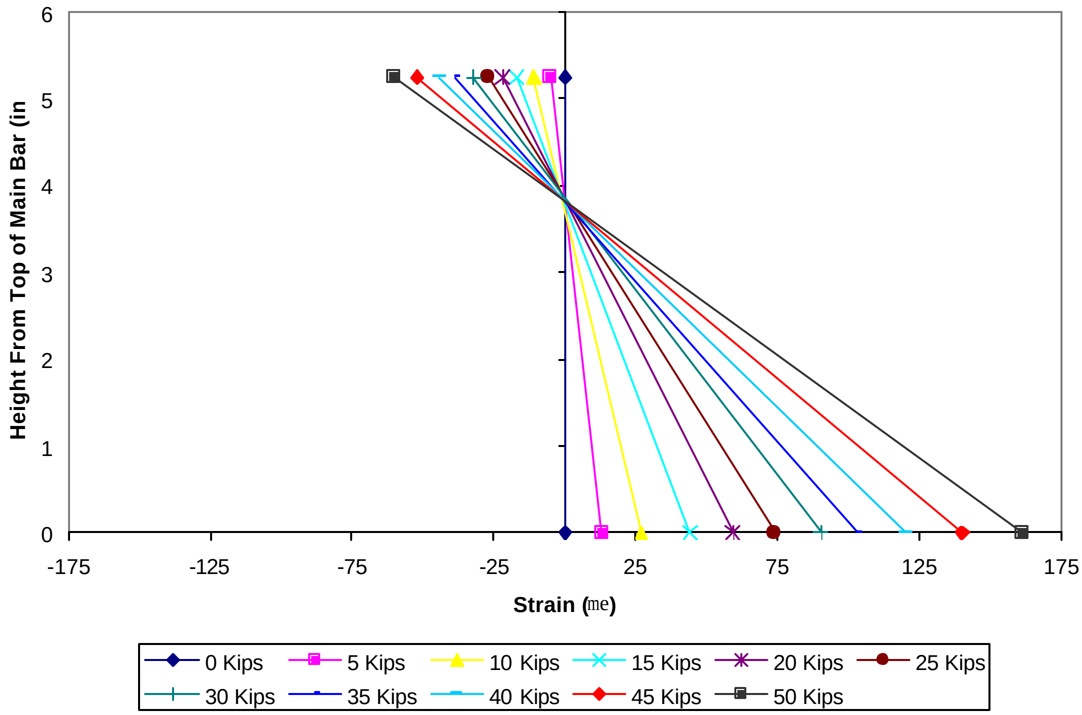

Figure B-344 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-1350K Cycles

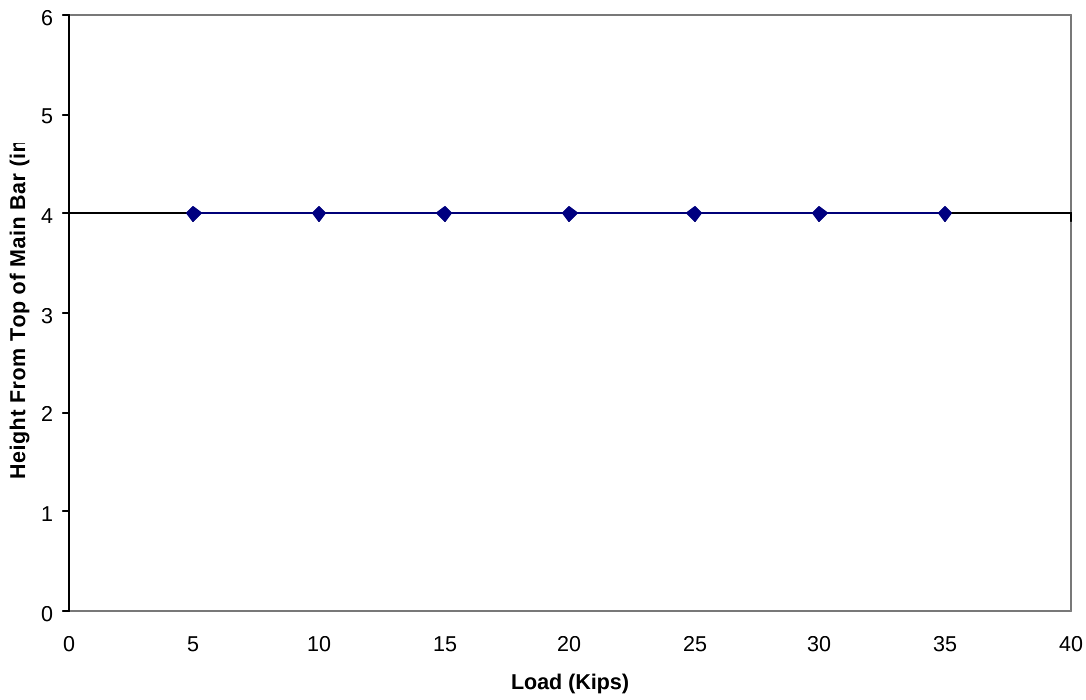

Figure B-345 Fatigue Specimen #2 Main Bar #2
-Neutral Axis Location-1350K Cycles

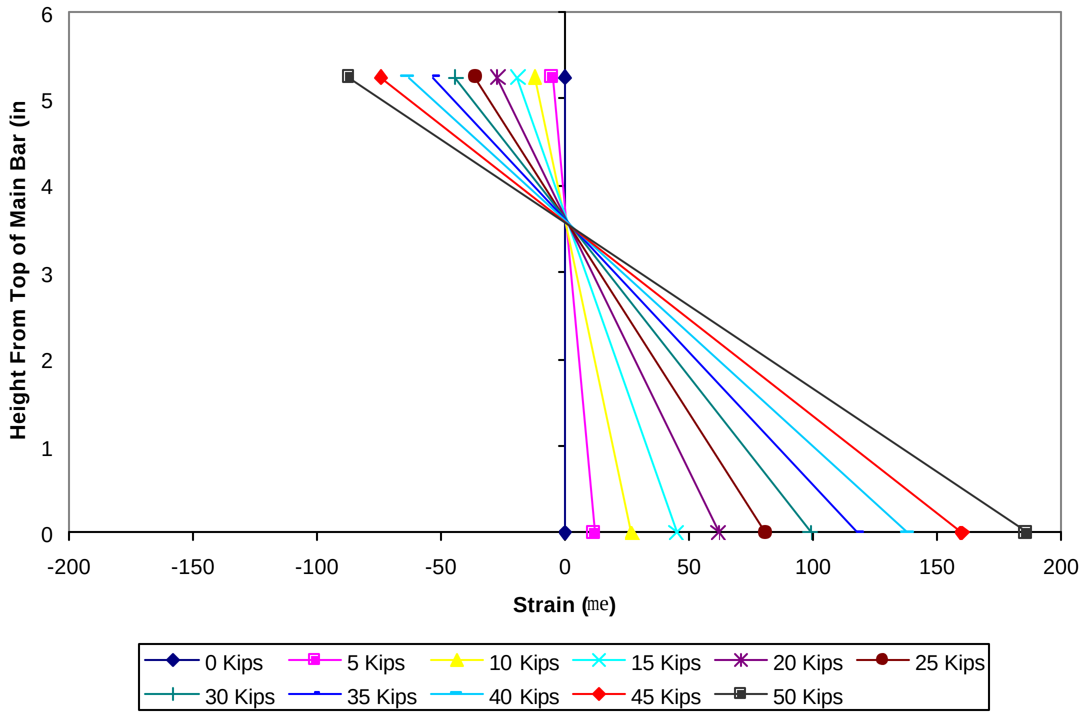

Figure B-346 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-1350K Cycles

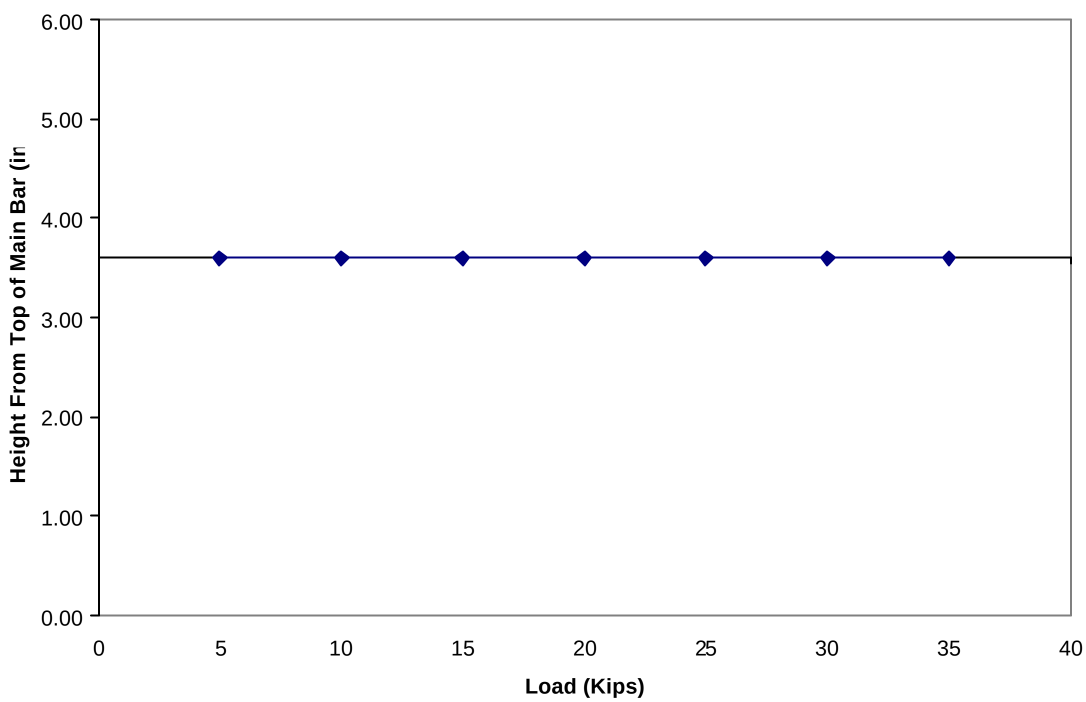

Figure B-347 Fatigue Specimen #2 Main Bar #3
-Neutral Axis Location-1350K Cycles

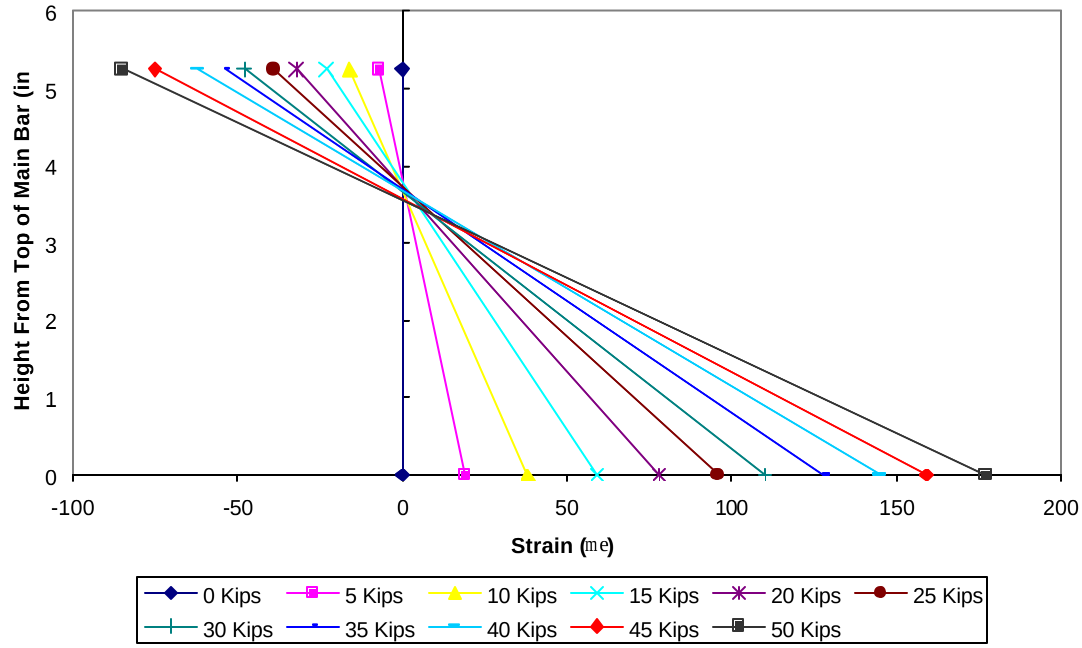

Figure B-348 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-1500K Cycles

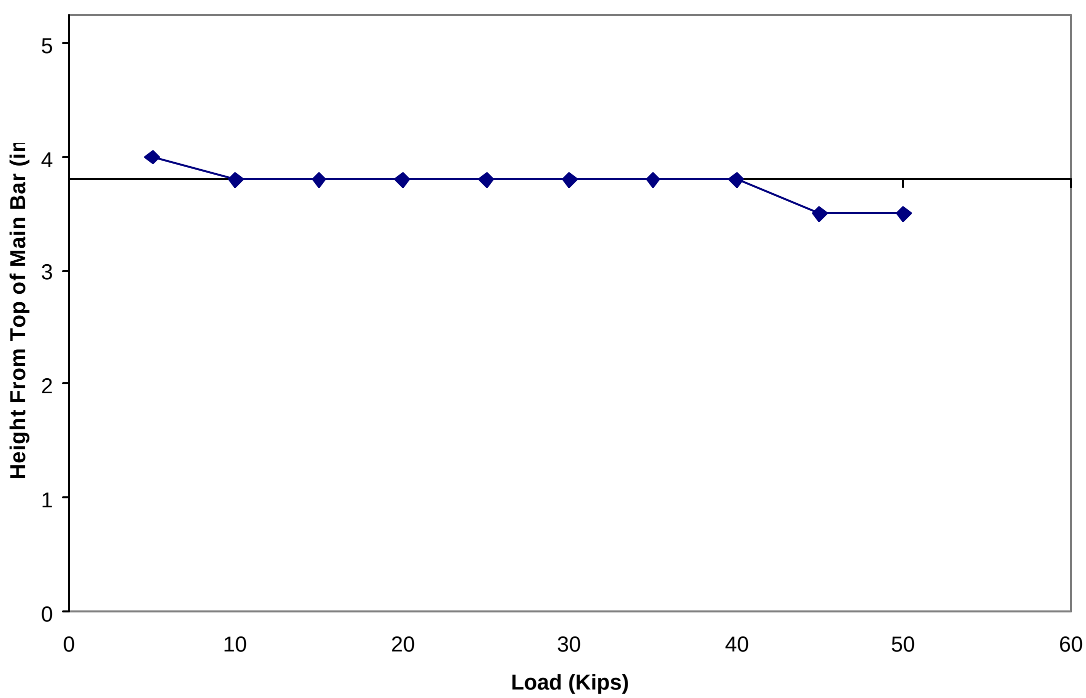

Figure B-349 Fatigue Specimen #2 Main Bar #1
-Neutral Axis Location-1500K Cycles

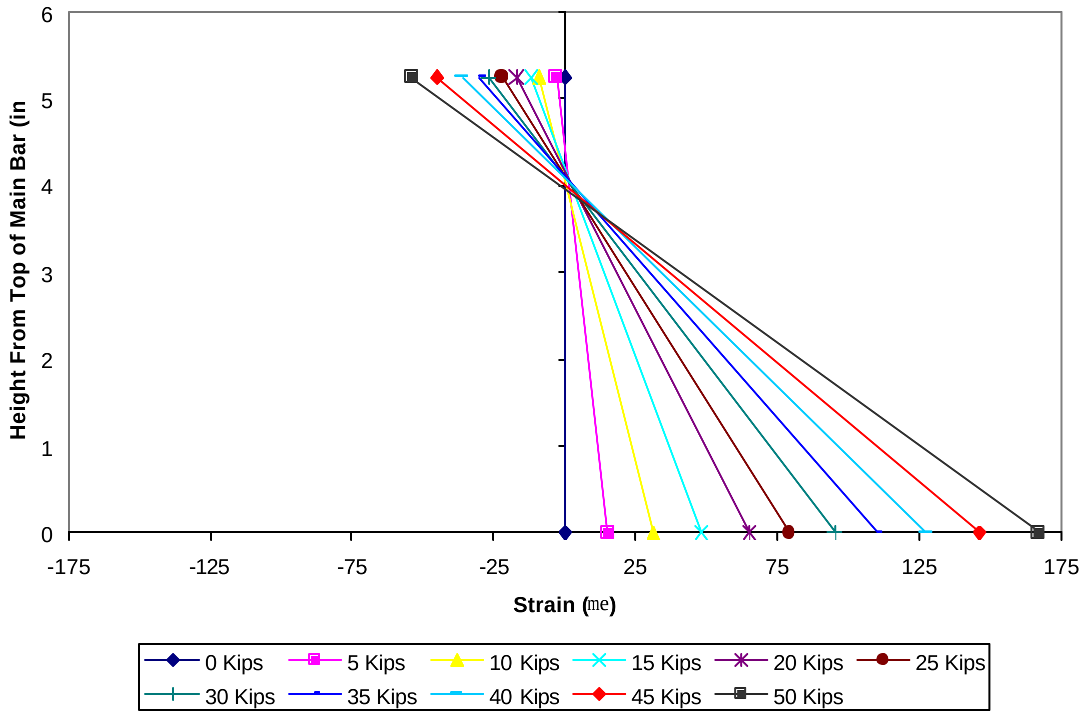

Figure B-350 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-1500K Cycles

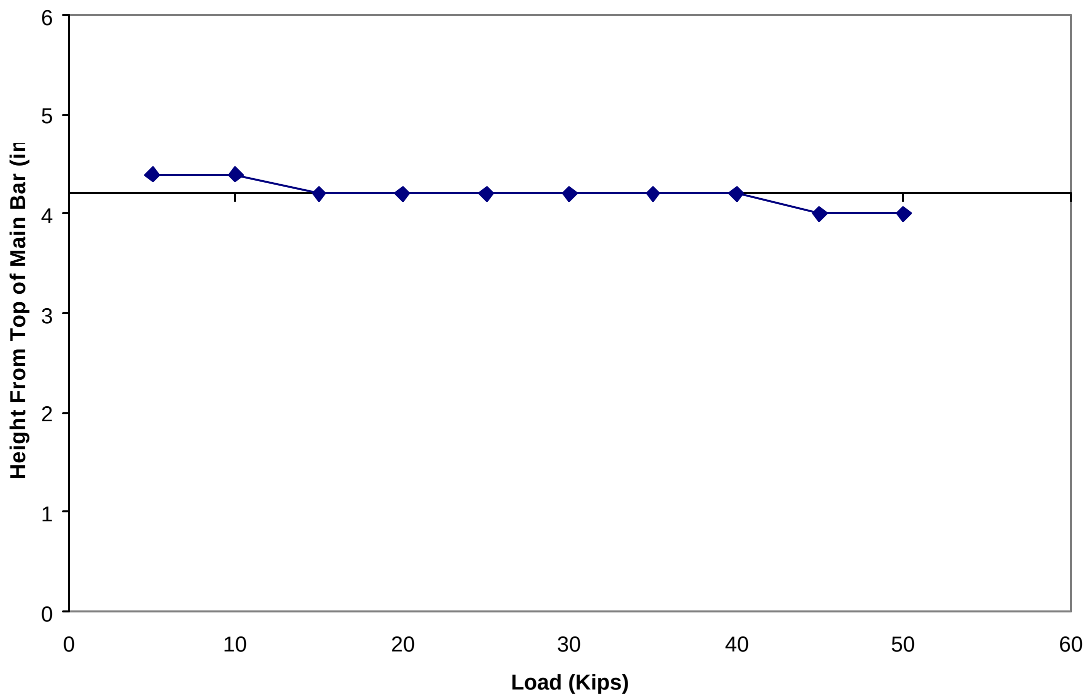

Figure B-351 Fatigue Specimen #2 Main Bar #2
-Neutral Axis Location-1500K Cycles

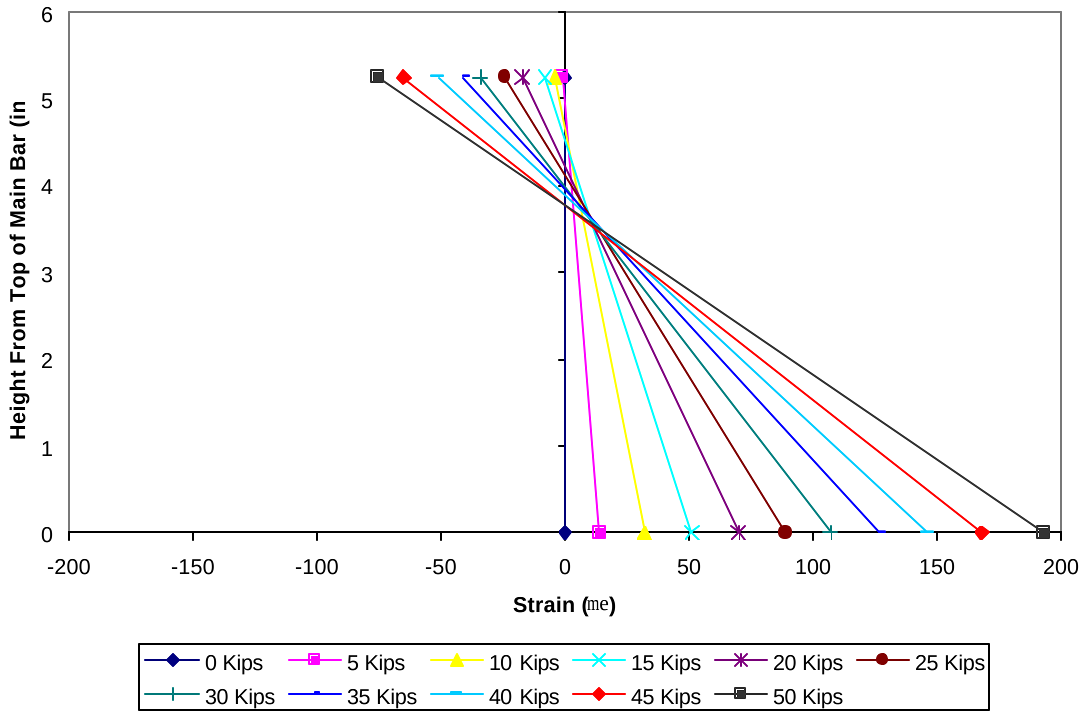

Figure B-352 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-1500K Cycles

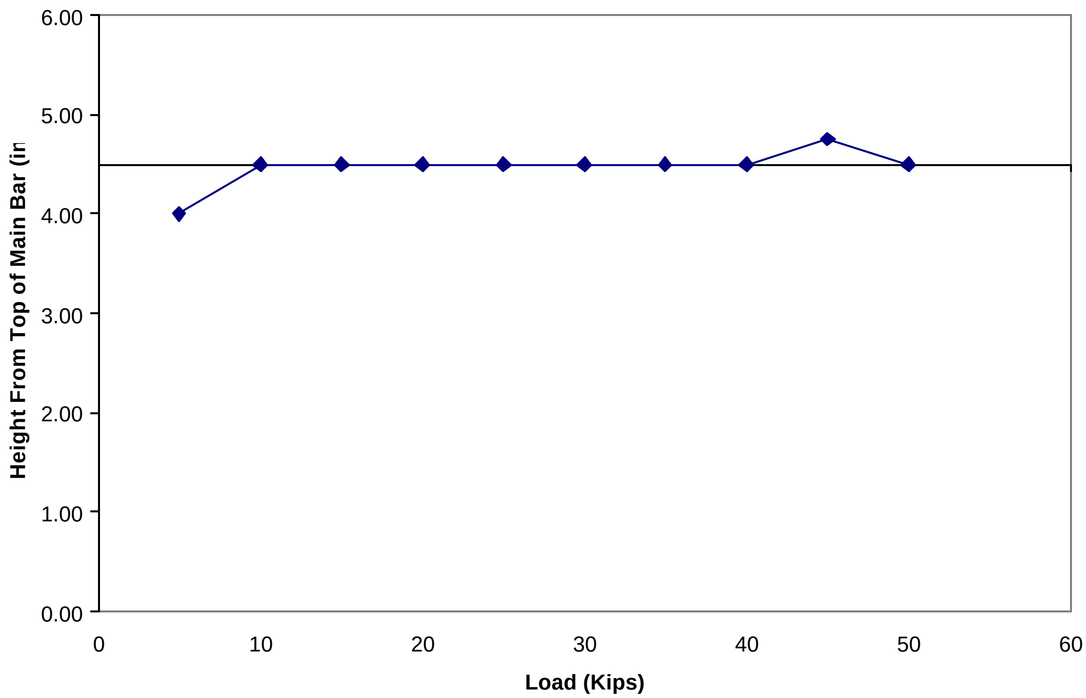

Figure B-353 Fatigue Specimen #2 Main Bar #3
-Neutral Axis Location-1500K Cycles

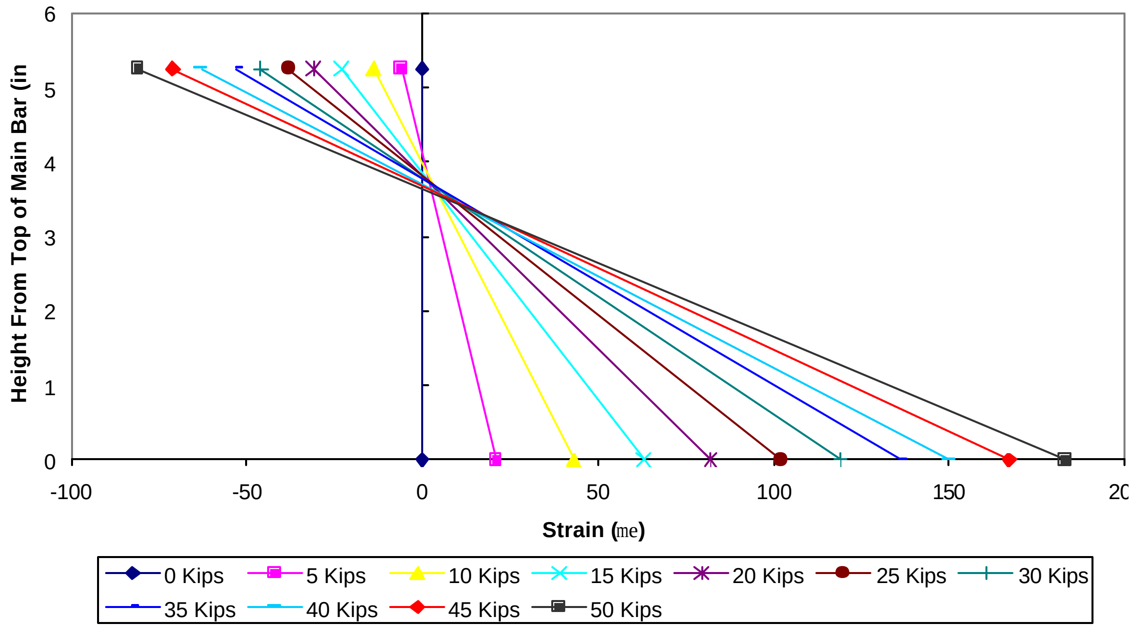

Figure B-354 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-1700K Cycles

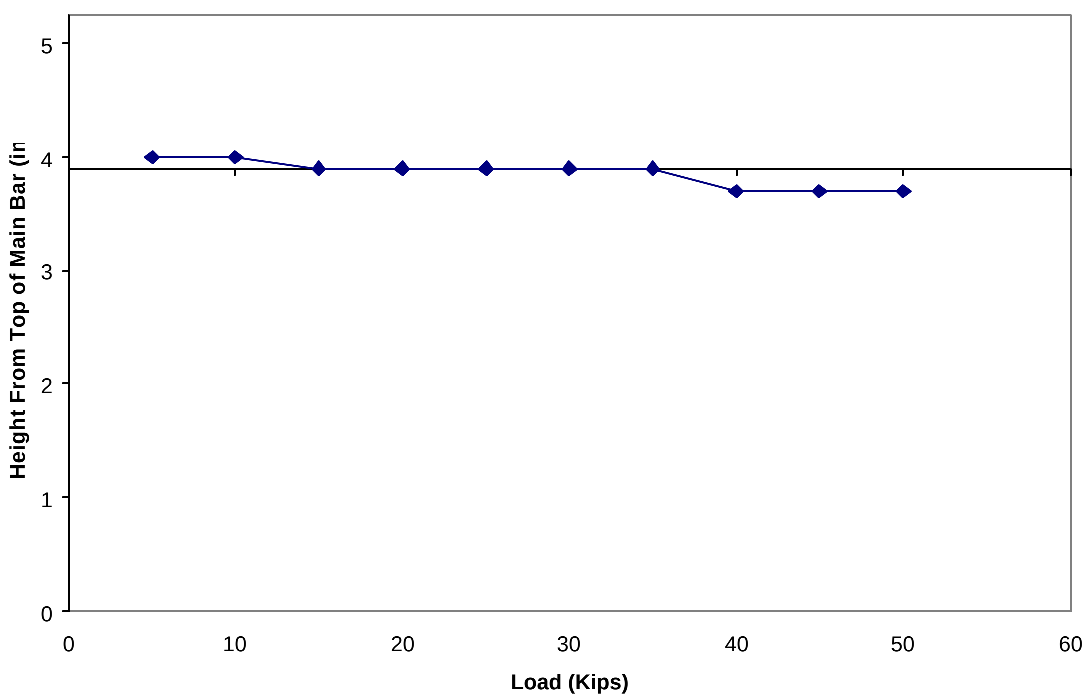

Figure B-355 Fatigue Specimen #2 Main Bar #1
-Neutral Axis Location-1700K Cycles

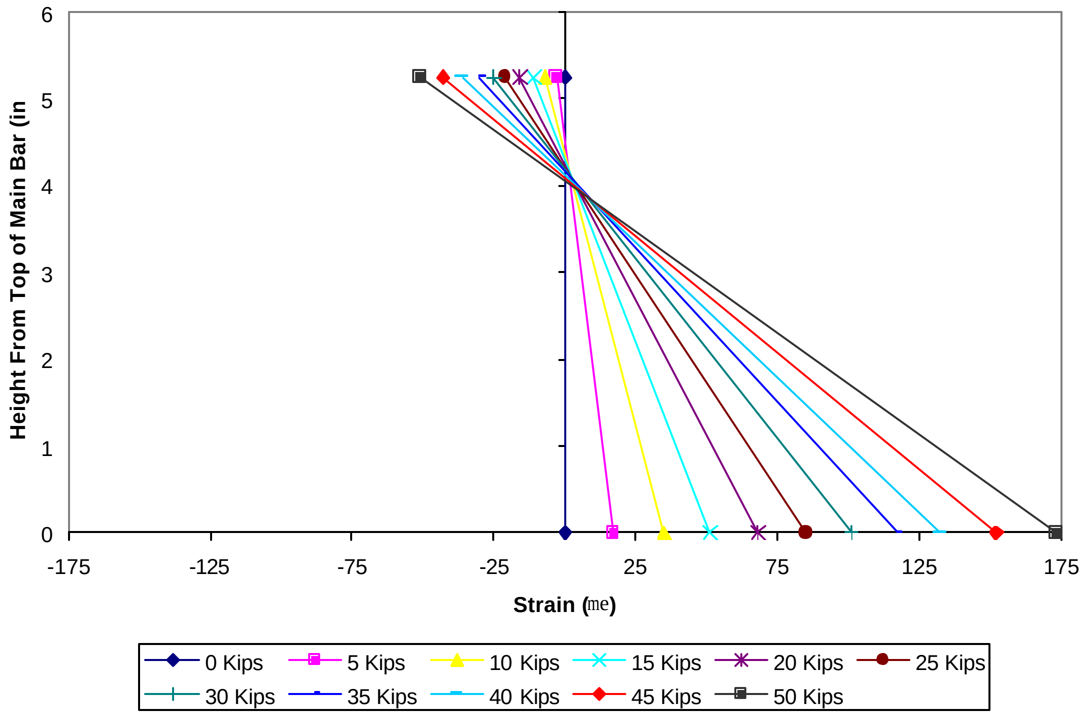

Figure B-356 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-1700K Cycles

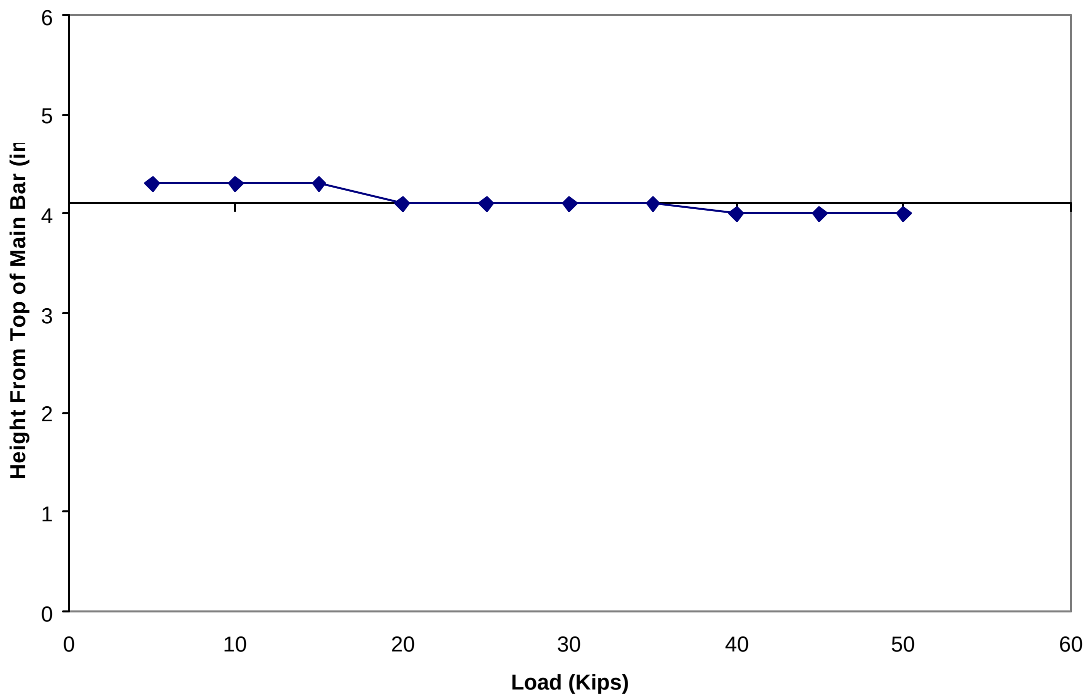

Figure B-357 Fatigue Specimen #2 Main Bar #2
-Neutral Axis Location-1700K Cycles

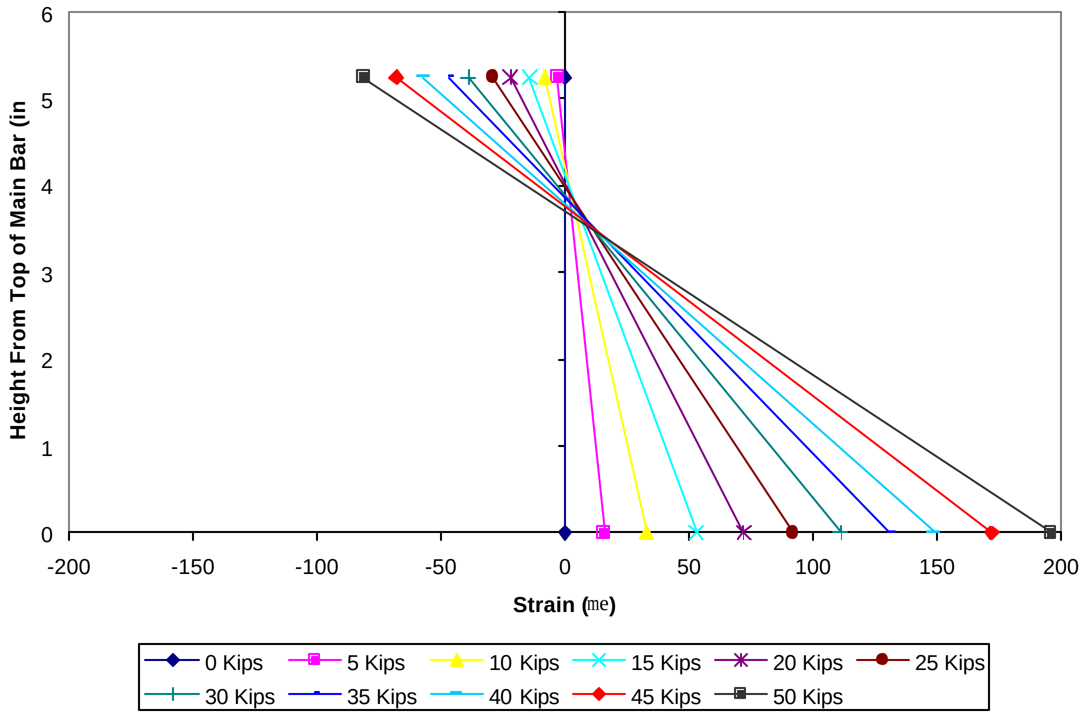

Figure B-358 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-1700K Cycles

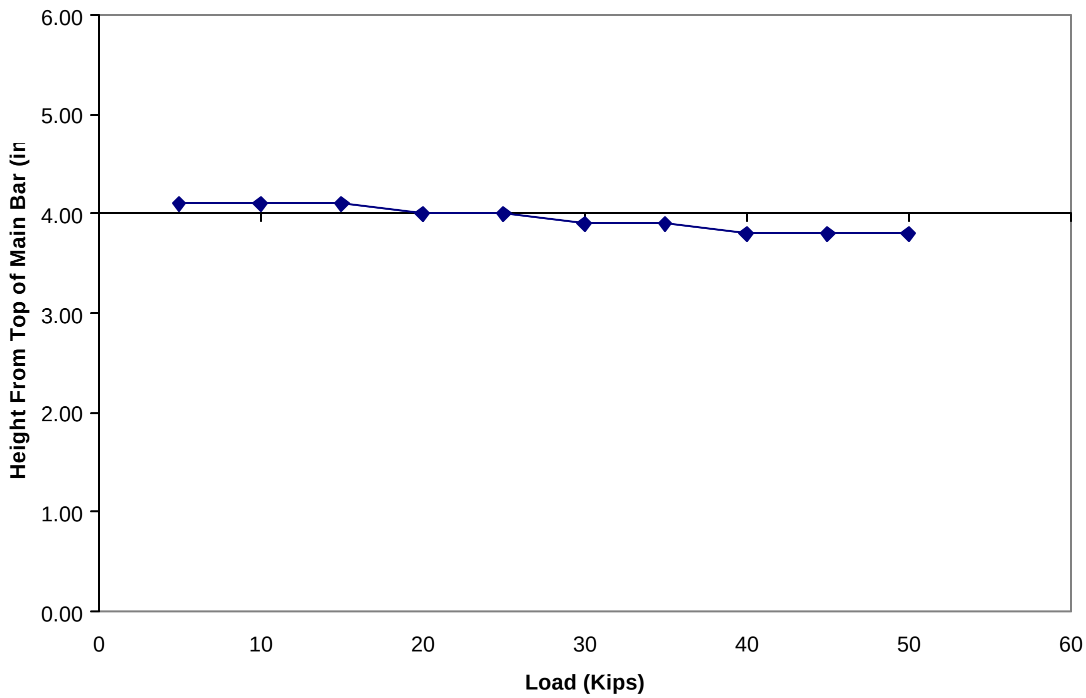

Figure B-359 Fatigue Specimen #2 Main Bar #3
-Neutral Axis Location-1700K Cycles

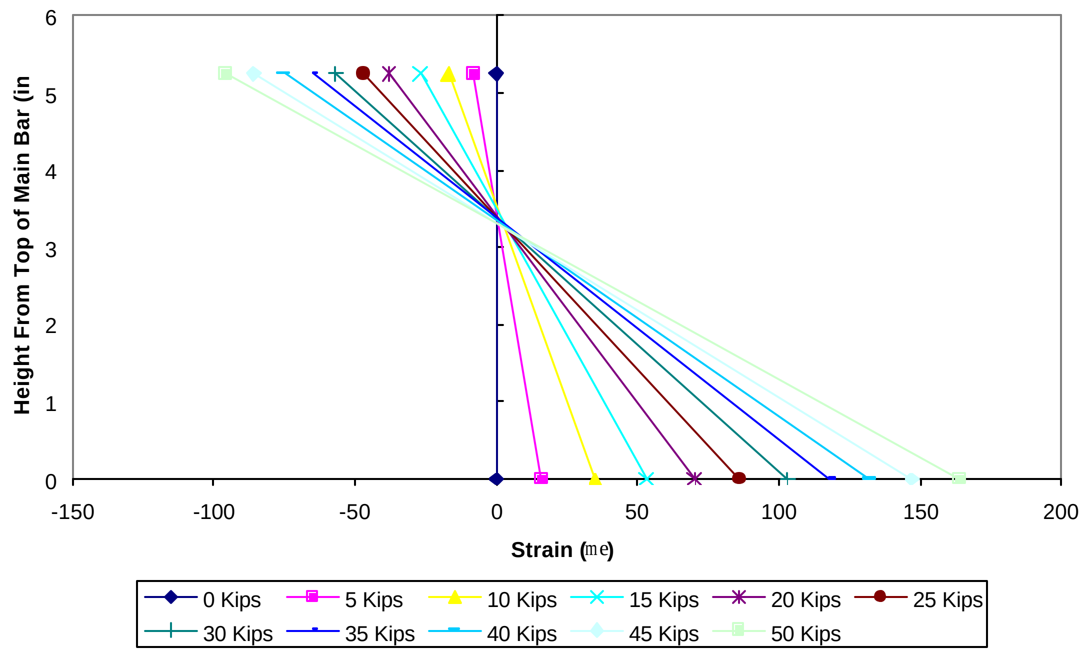

Figure B-360 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-1850K Cycles

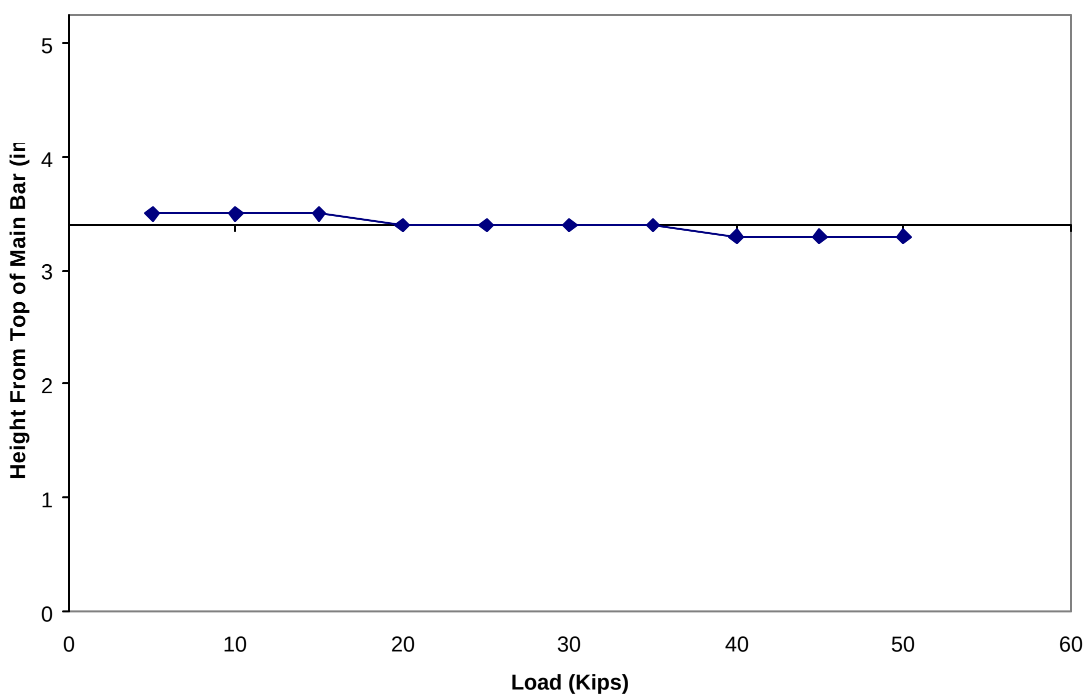

Figure B-361 Fatigue Specimen #2 Main Bar #1
-Neutral Axis Location-1850K Cycles

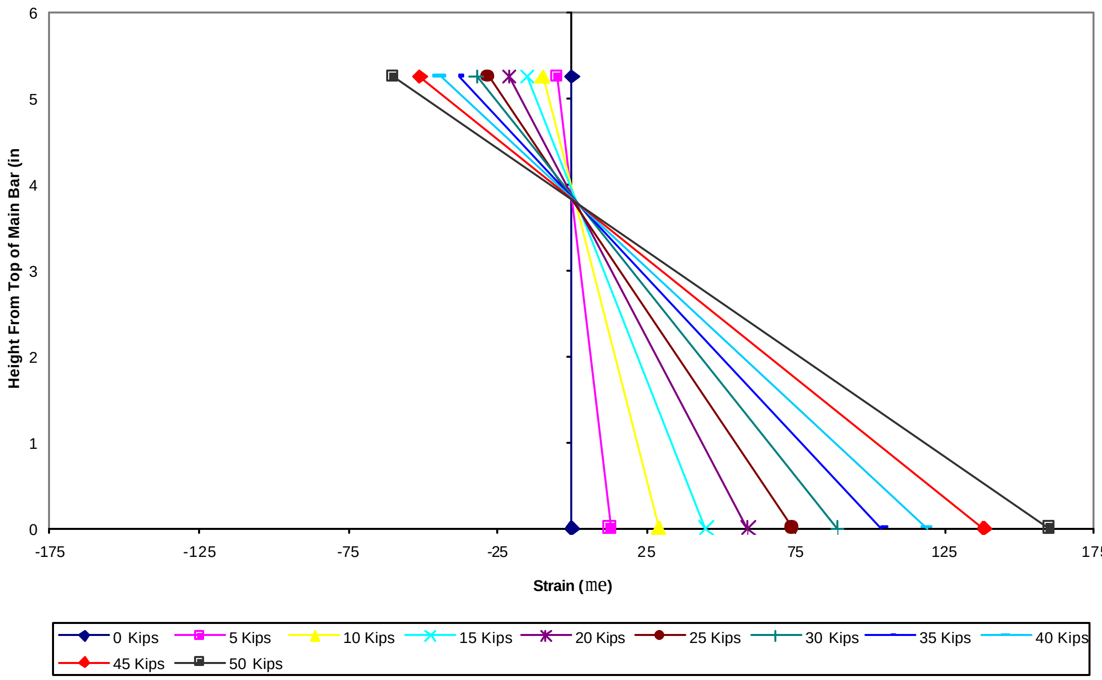

Figure B-362 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-1850K Cycles

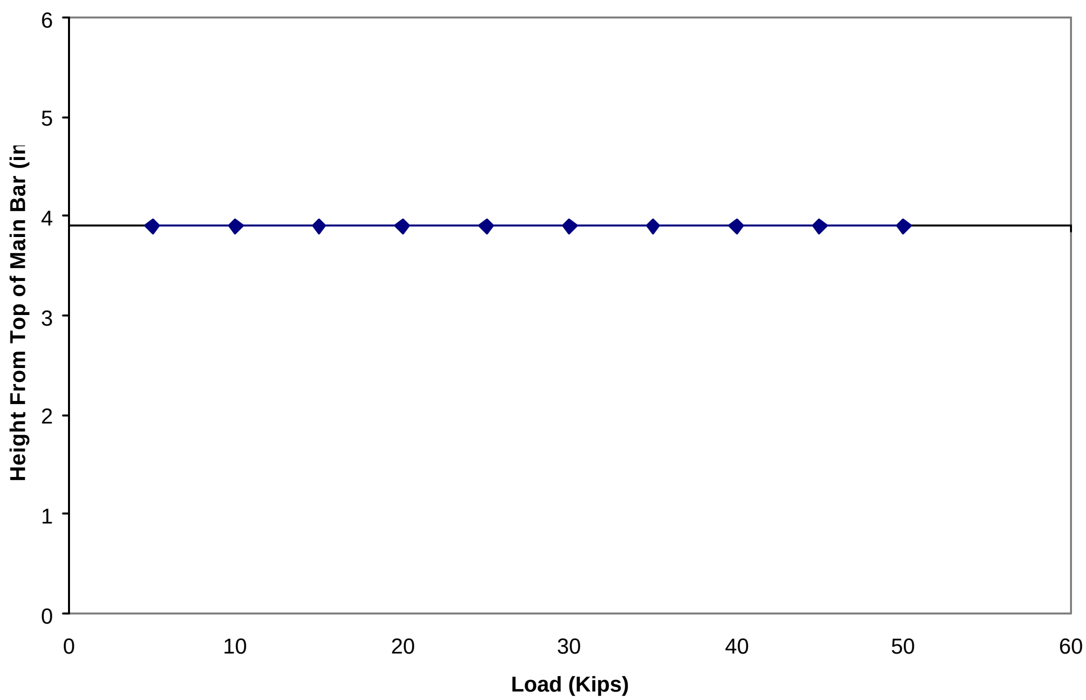

Figure B-363 Fatigue Specimen #2 Main Bar #2
-Neutral Axis Location-1850K Cycles

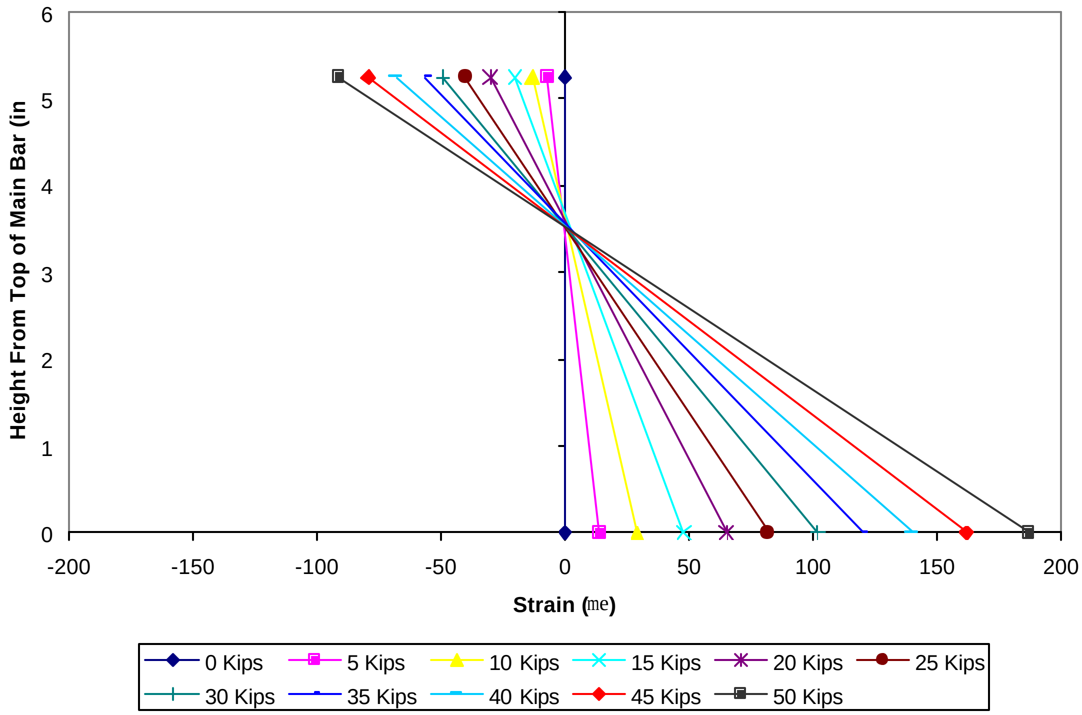

Figure B-364 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-1850K Cycles

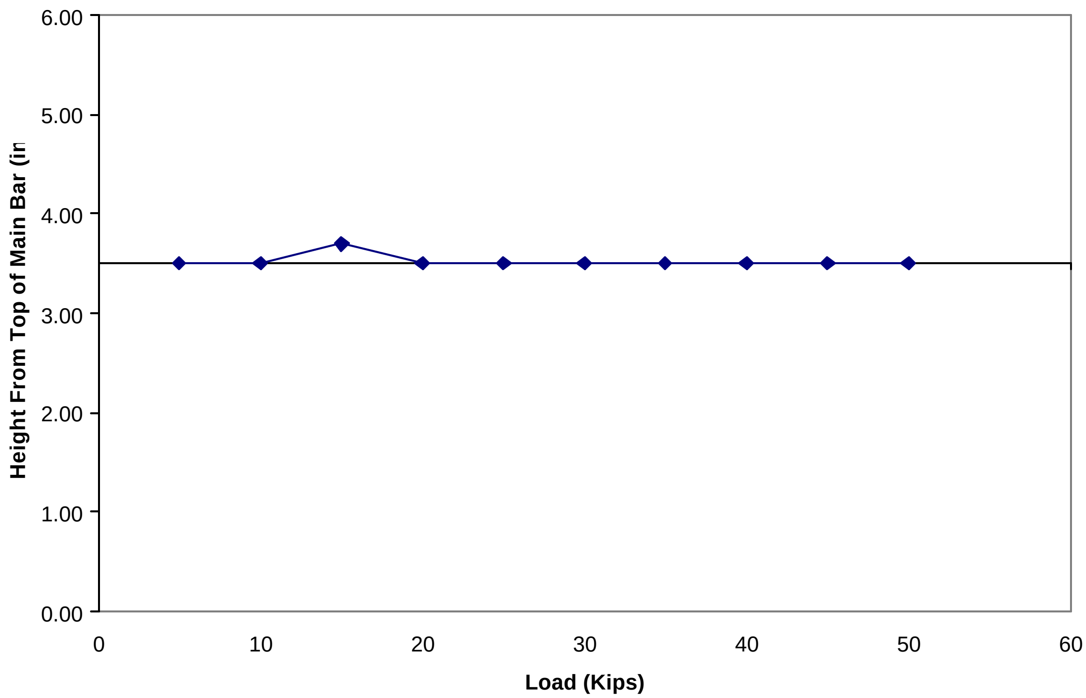

Figure B-365 Fatigue Specimen #2 Main Bar #3
-Neutral Axis Location-1850K Cycles

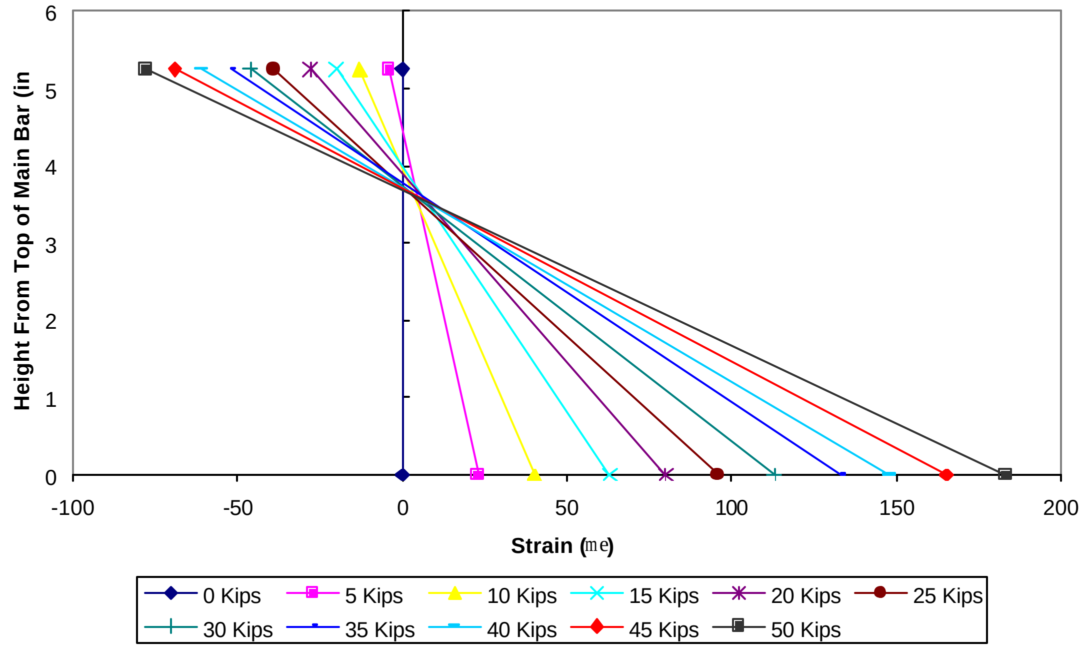

Figure B-366 Fatigue Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution-2000K Cycles

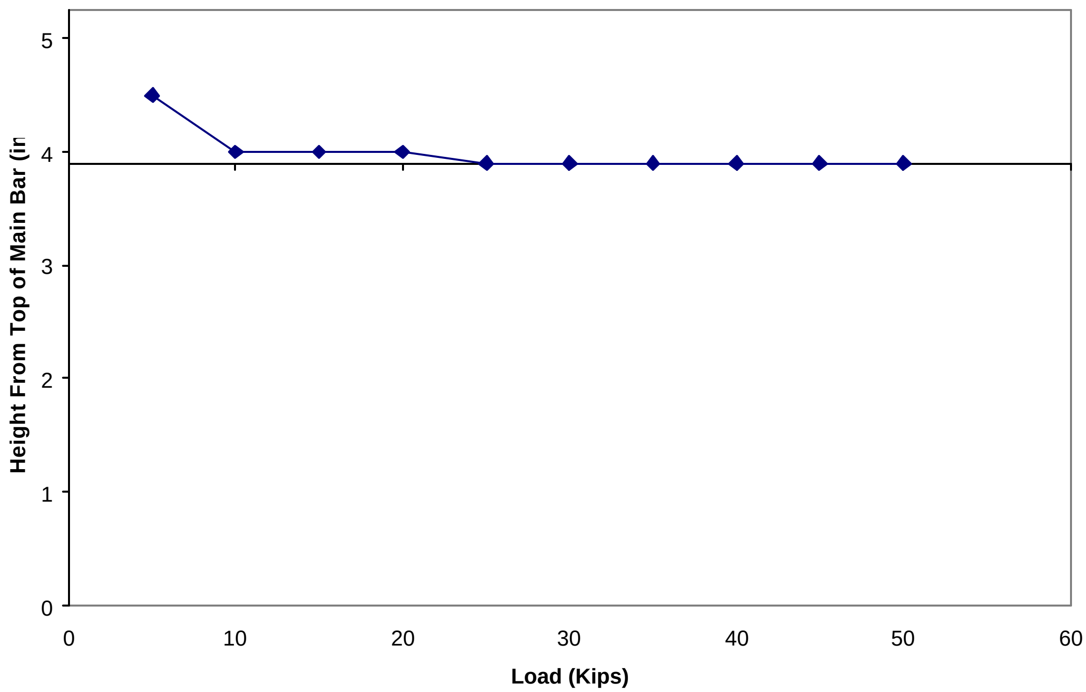

Figure B-367 Fatigue Specimen #2 Main Bar #1
-Neutral Axis Location-2000K Cycles

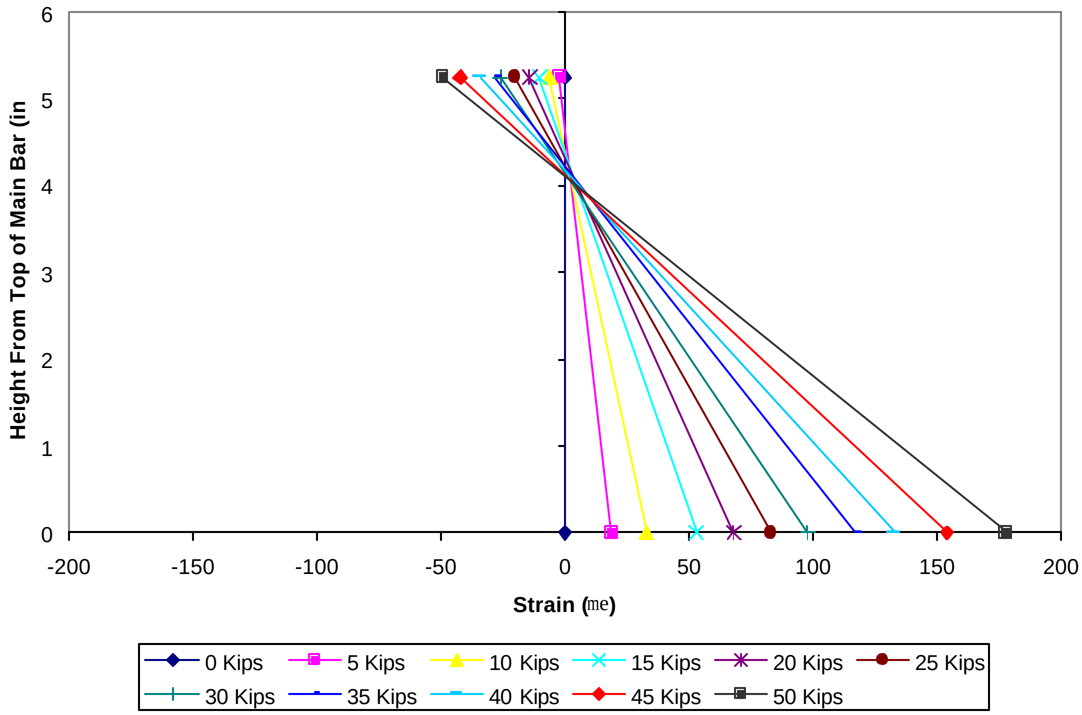

Figure B-368 Fatigue Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution-2000K Cycles

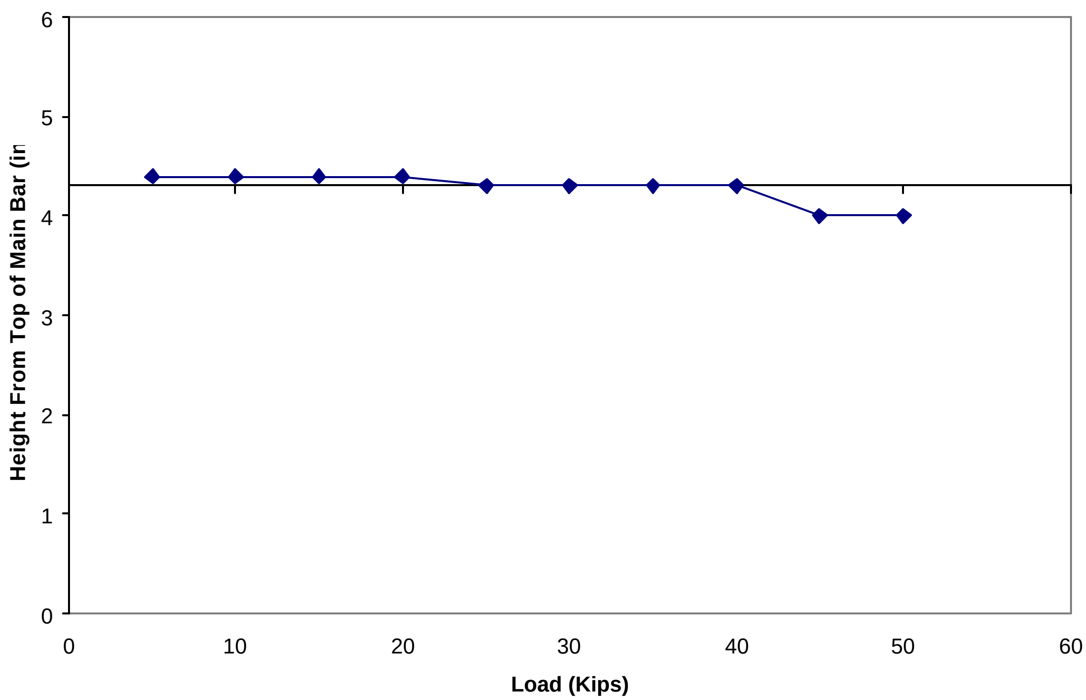

Figure B-369 Fatigue Specimen #2 Main Bar #2
-Neutral Axis Location-2000K Cycles

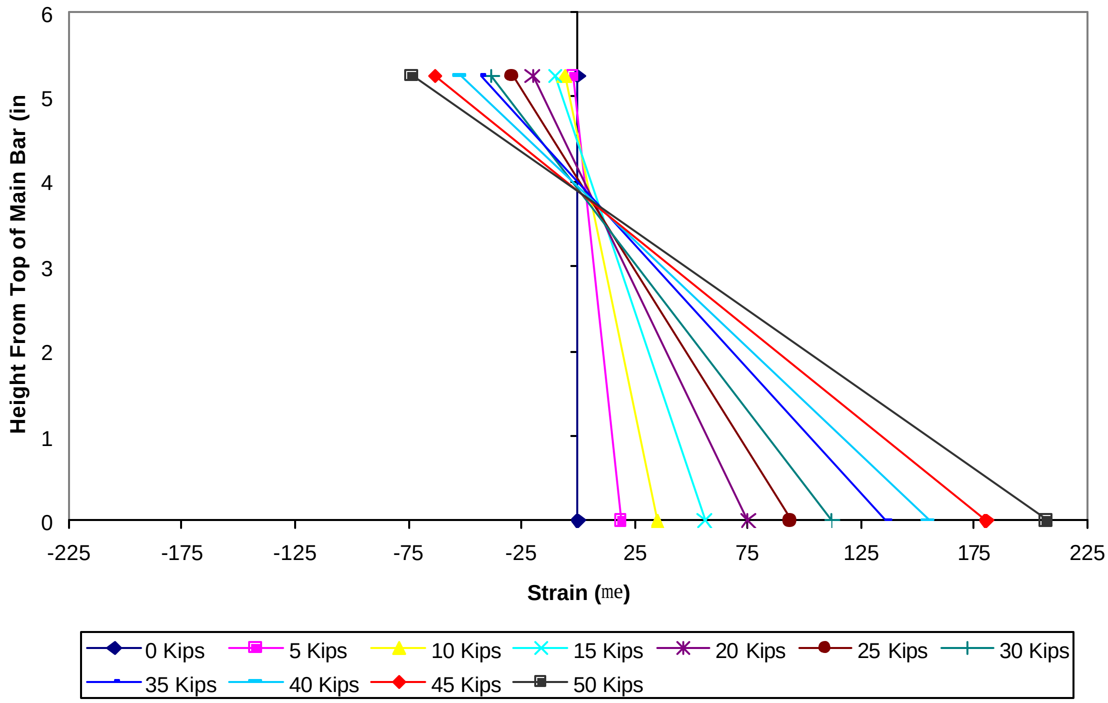

Figure B-370 Fatigue Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution-2000K Cycles

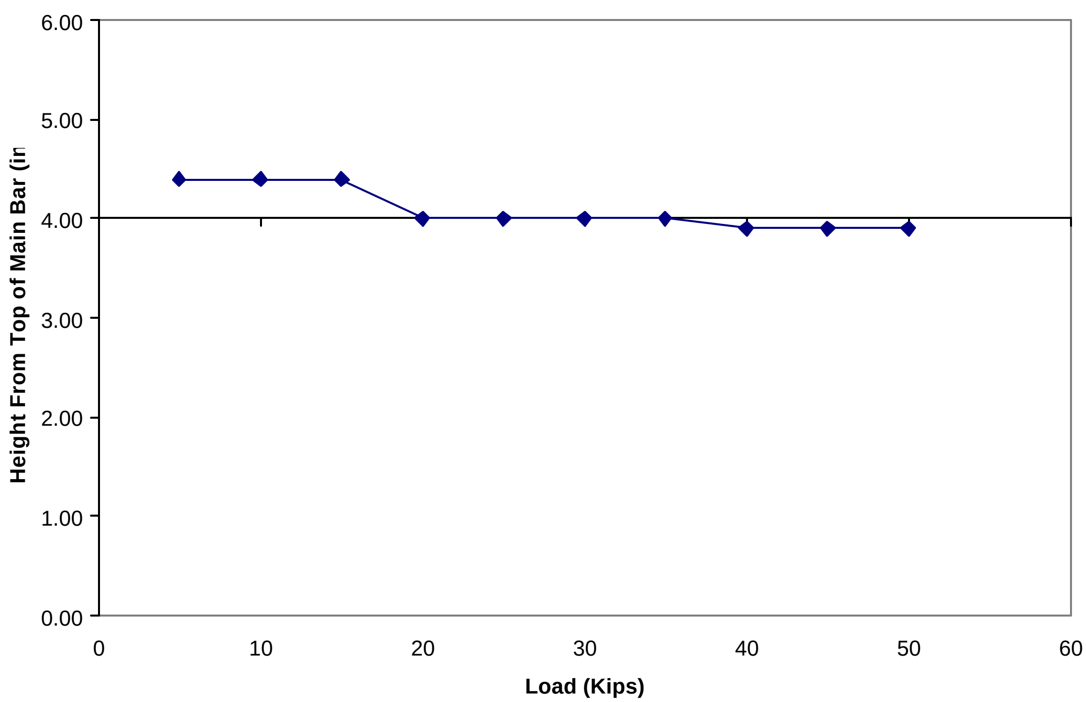

Figure B-371 Fatigue Specimen #2 Main Bar #3
-Neutral Axis Location-2000K Cycles

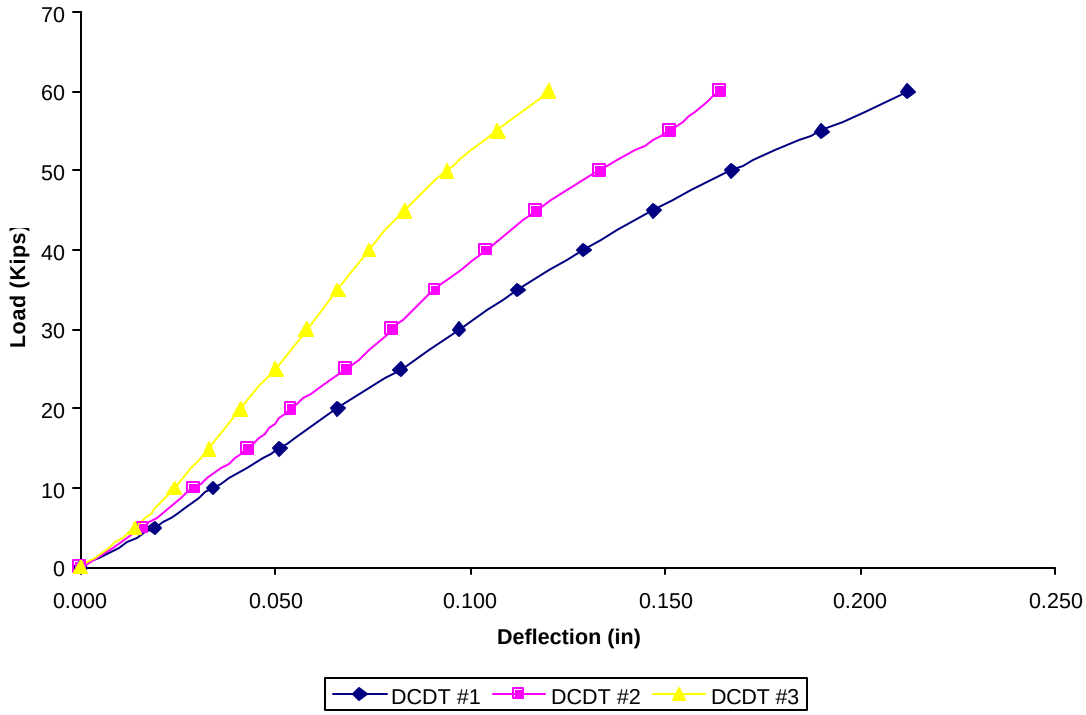

Figure B-372 Ultimate Strength Specimen #1
-Deflection-South Span

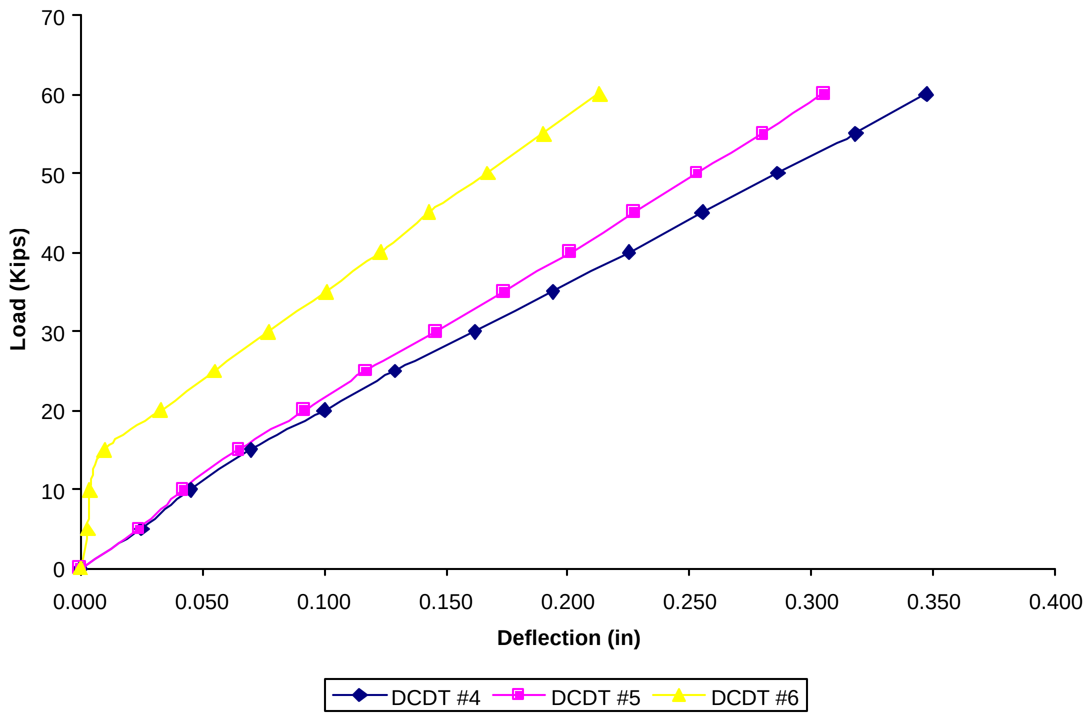

Figure B-373 Ultimate Strength Specimen #1
-Deflection-North Span

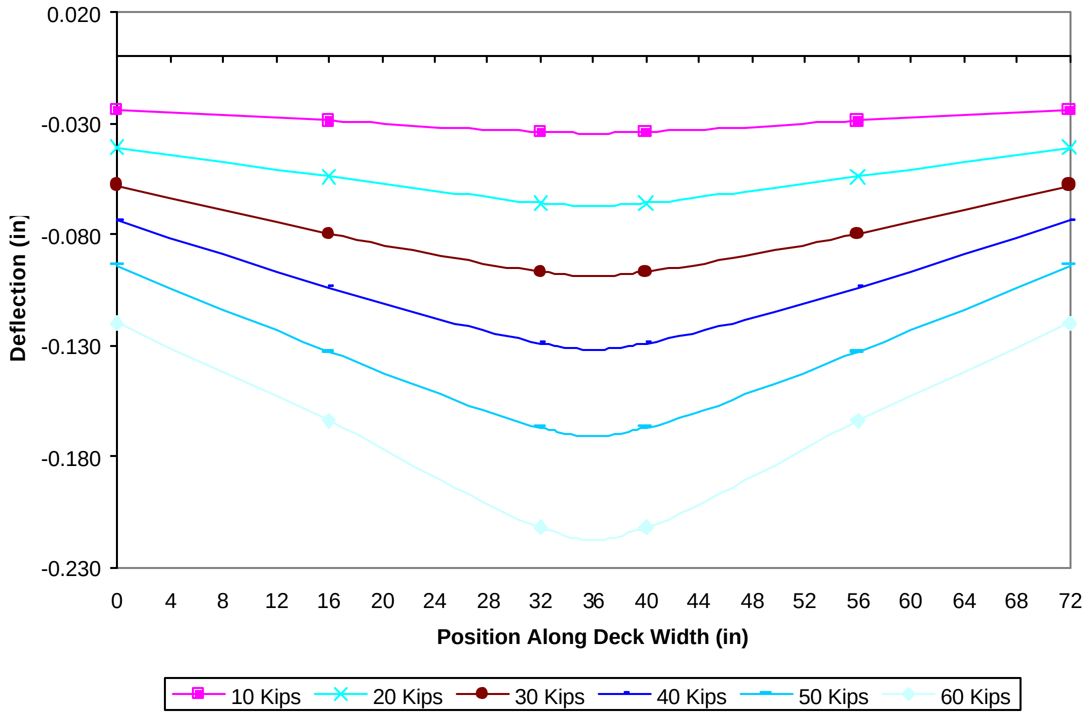

Figure B-374 Ultimate Strength Specimen #1
-Deflection Profile-South Span

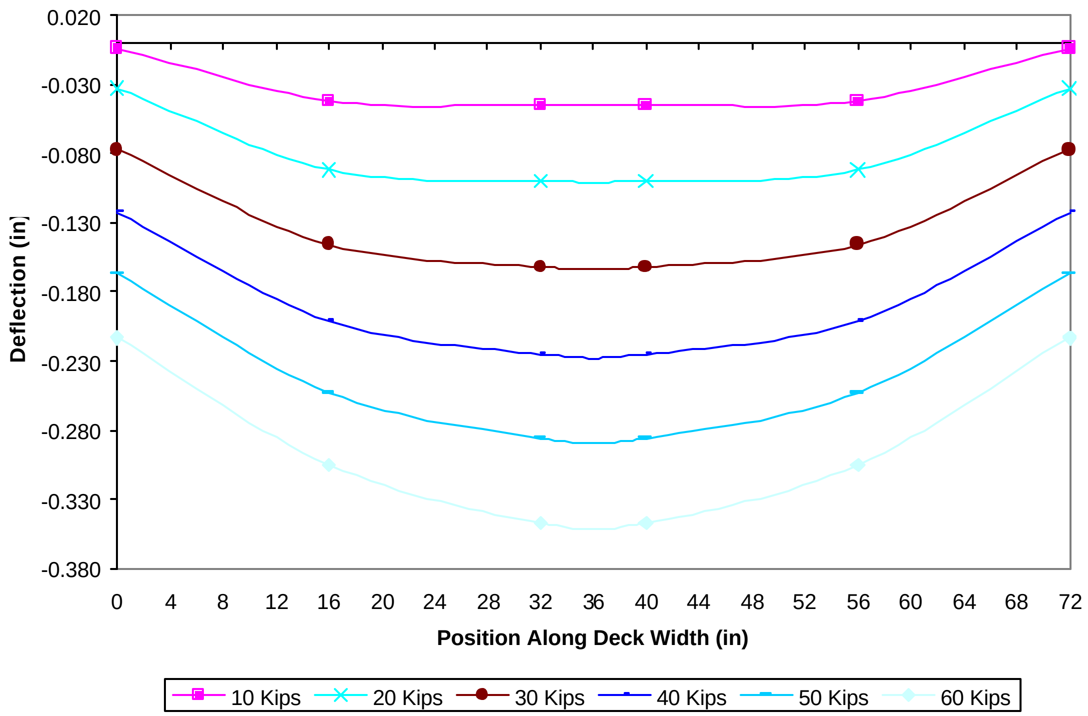

Figure B-375 Ultimate Strength Specimen #1
-Deflection-North Span

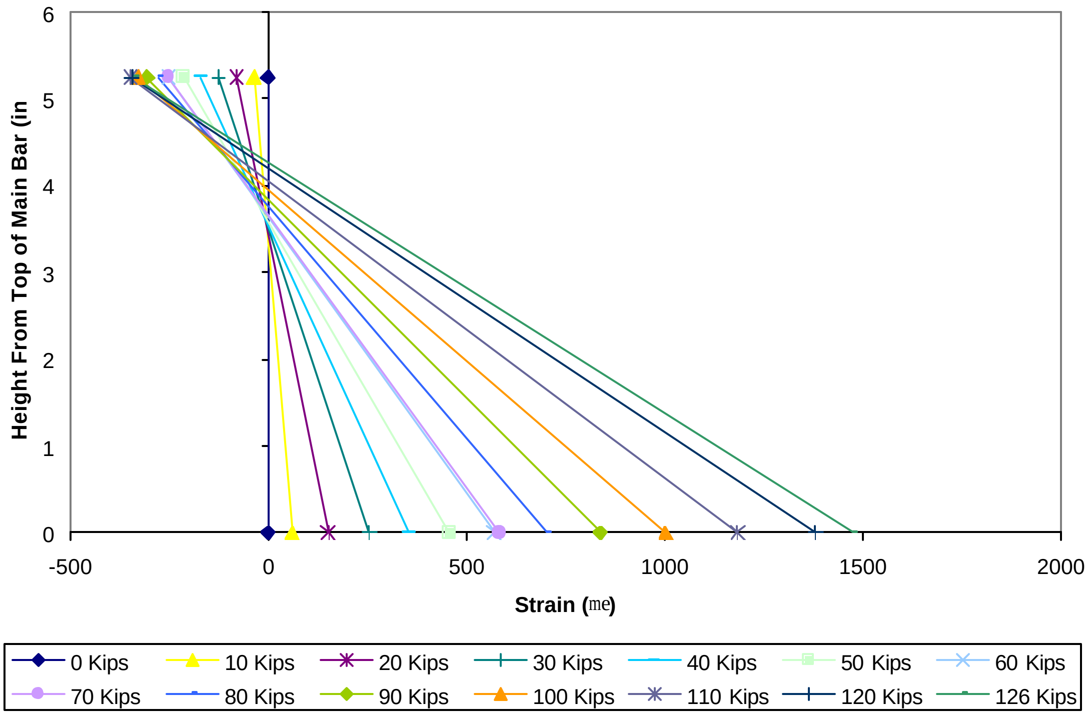

Figure B-376 Ultimate Strength Specimen #1 Main Bar #1
-Cross-Sectional Strain Distribution

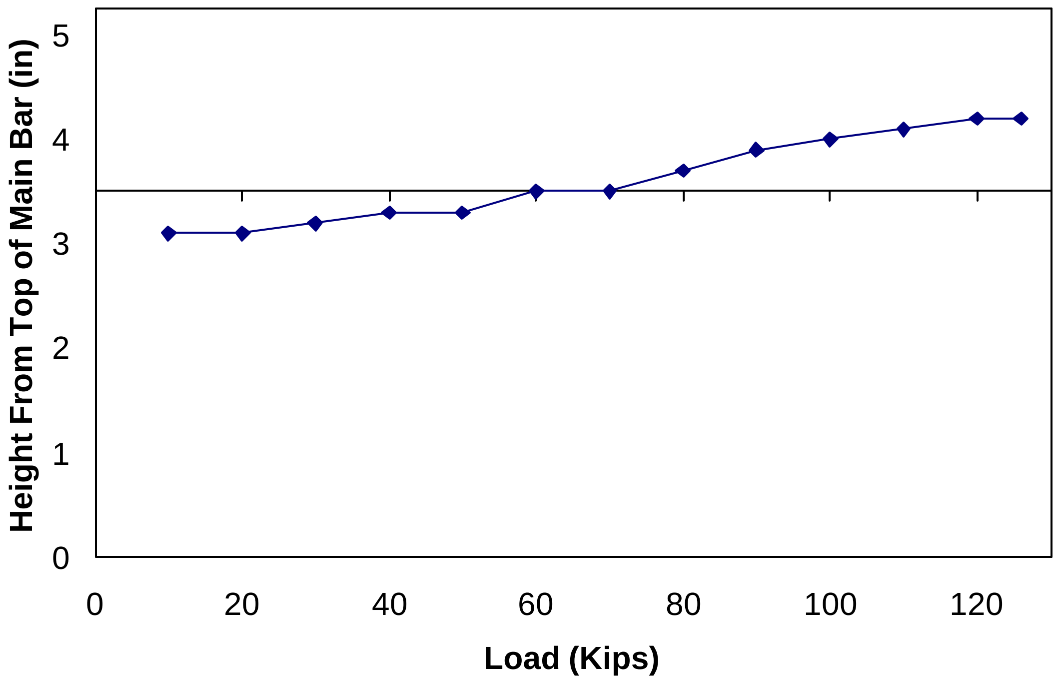

Figure B-377 Ultimate Strength Specimen #1 Main Bar #1
-Neutral Axis Location

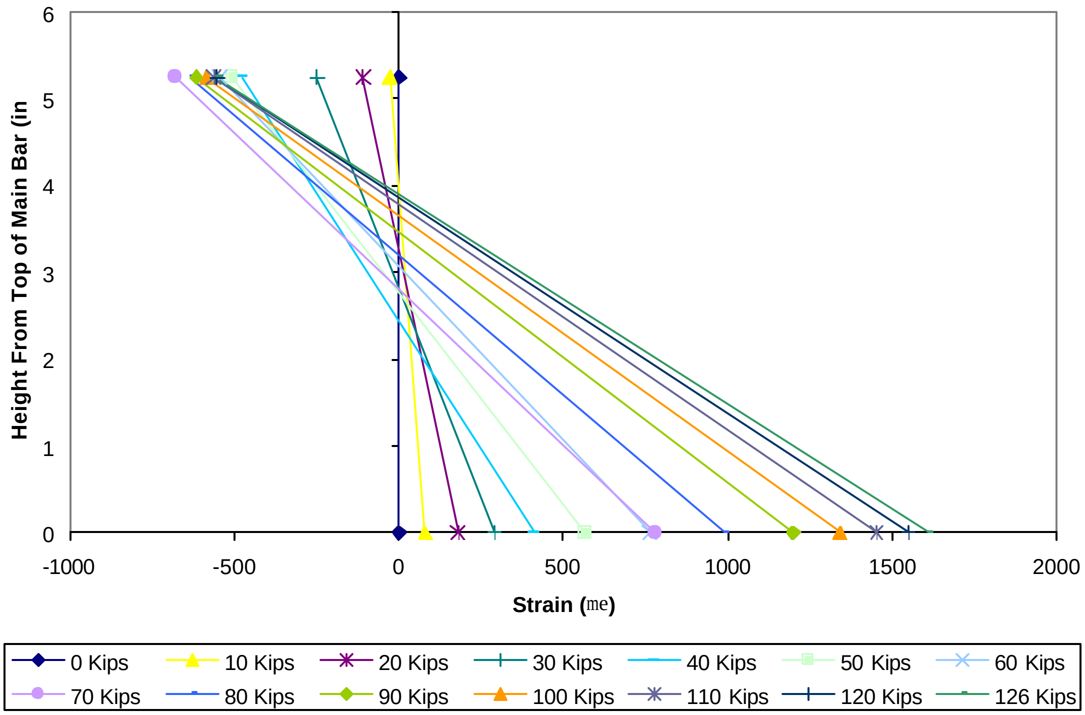

Figure B-378 Ultimate Strength Specimen #1 Main Bar #2
-Cross-Sectional Strain Distribution

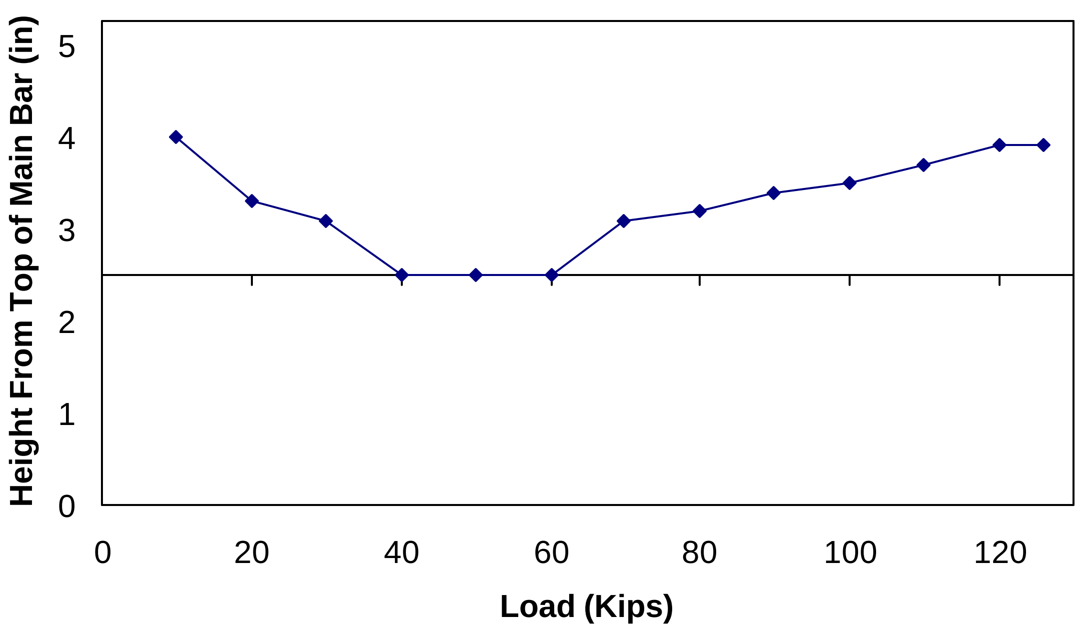

Figure B-379 Ultimate Strength Specimen #1 Main Bar #2
-Neutral Axis Location

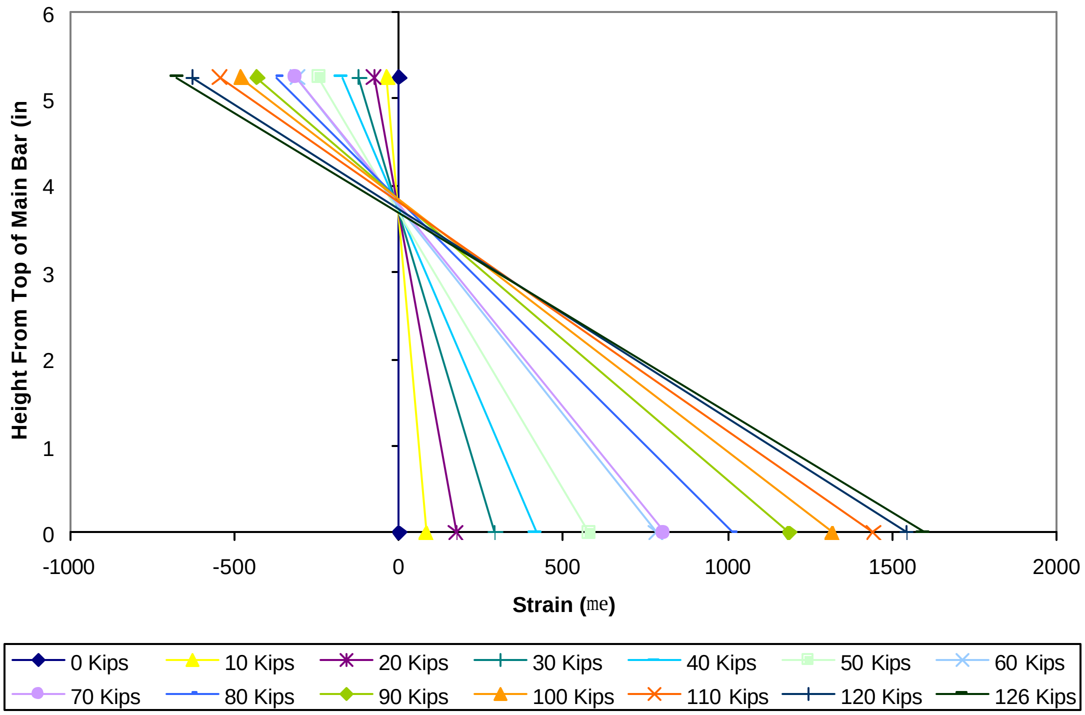

Figure B-380 Ultimate Strength Specimen #1 Main Bar #3
-Cross-Sectional Strain Distribution

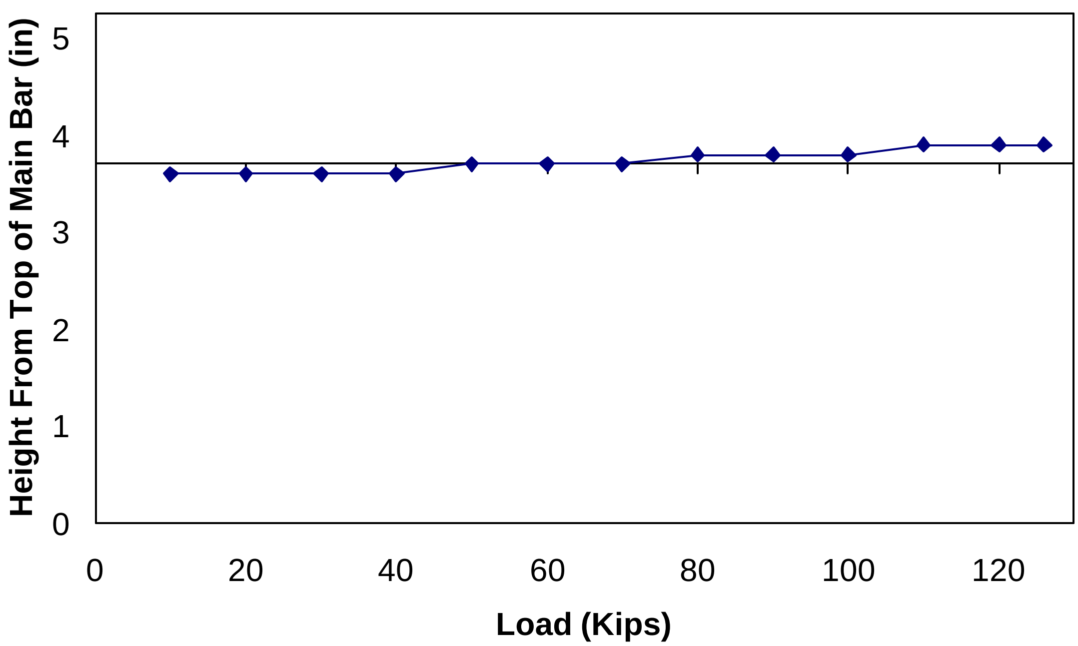

Figure B-381 Ultimate Strength Specimen #1 Main Bar #3
-Neutral Axis Location

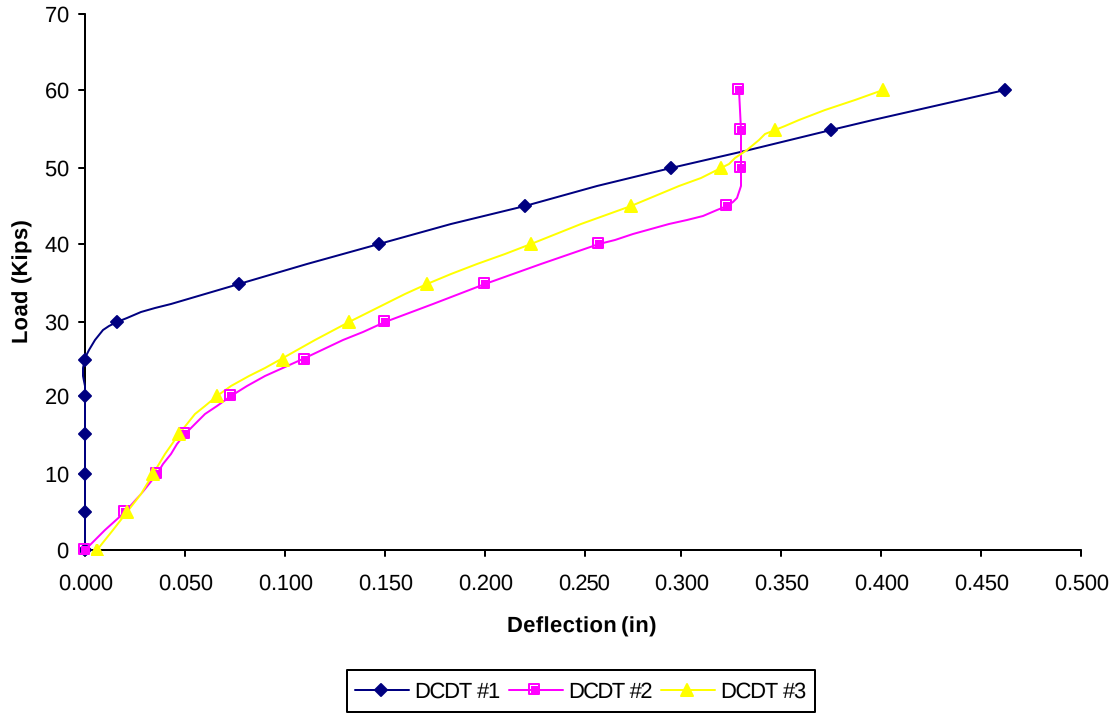

Figure B-382 Ultimate Strength Specimen #2
-Deflection-South Span

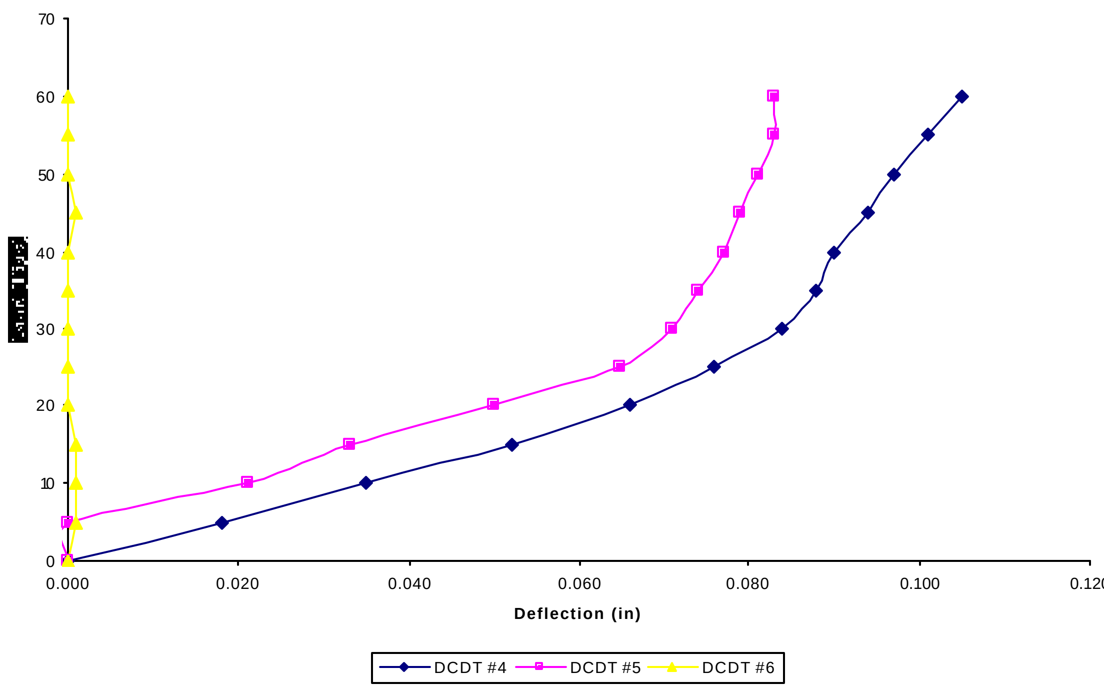

Figure B-383 Ultimate Strength Specimen #2
-Deflection-North Span

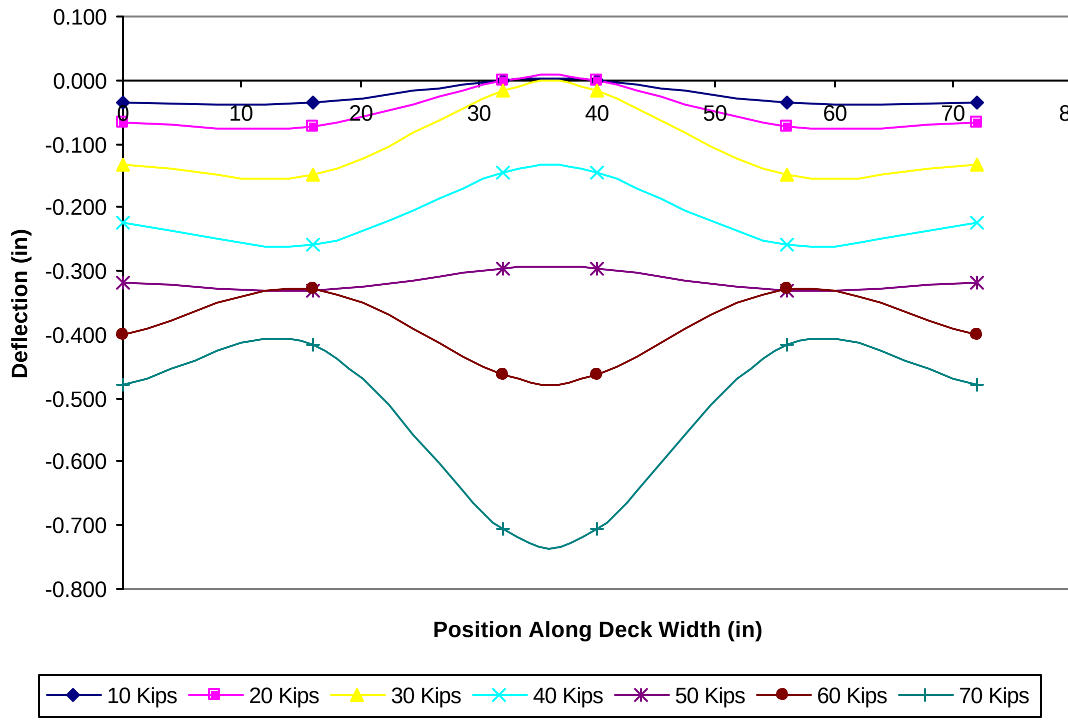

Figure B-384 Ultimate Strength Specimen #2
-Deflection Profile-South Span

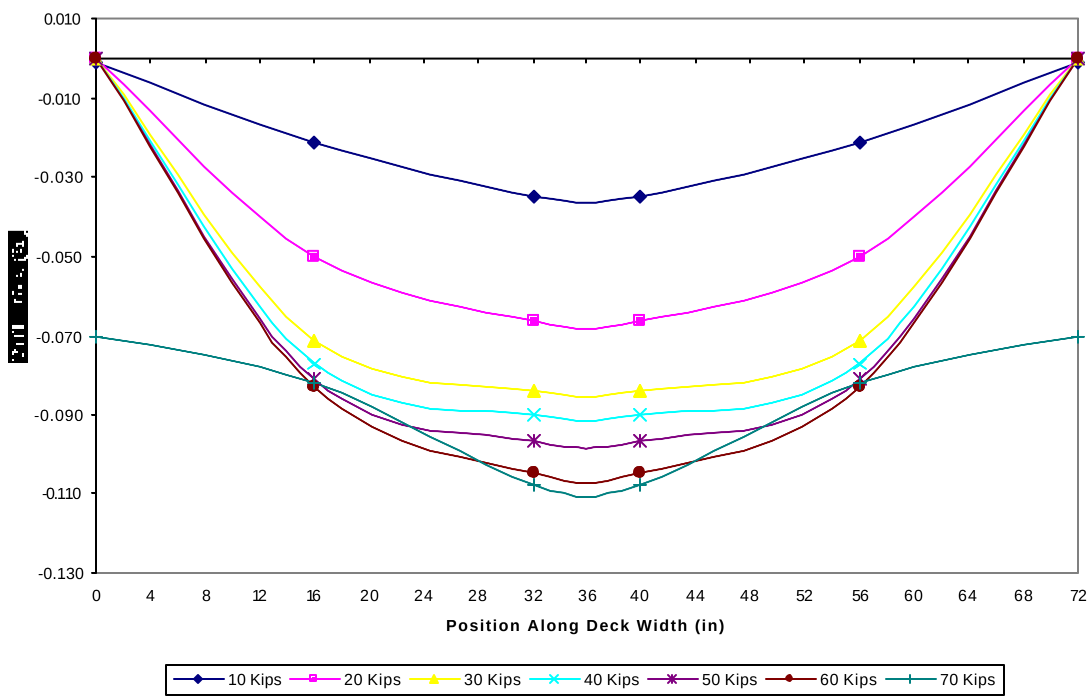

Figure B-385 Ultimate Strength Specimen #2
-Deflection-North Span

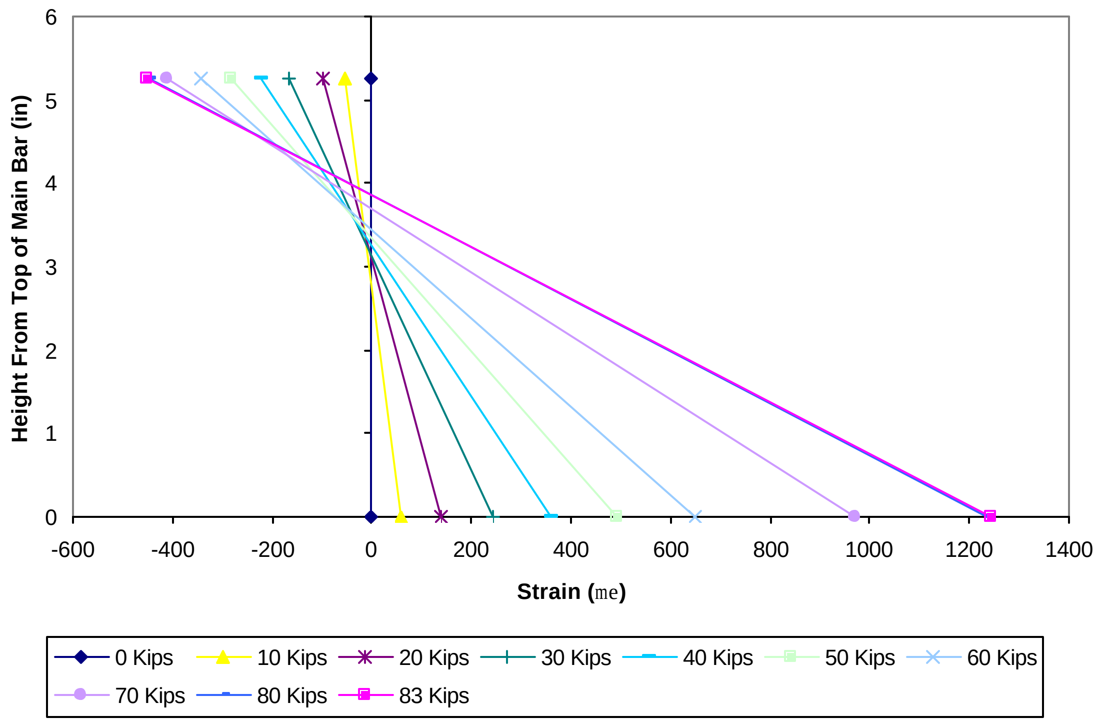

Figure B-386 Ultimate Strength Specimen #2 Main Bar #1
-Cross-Sectional Strain Distribution

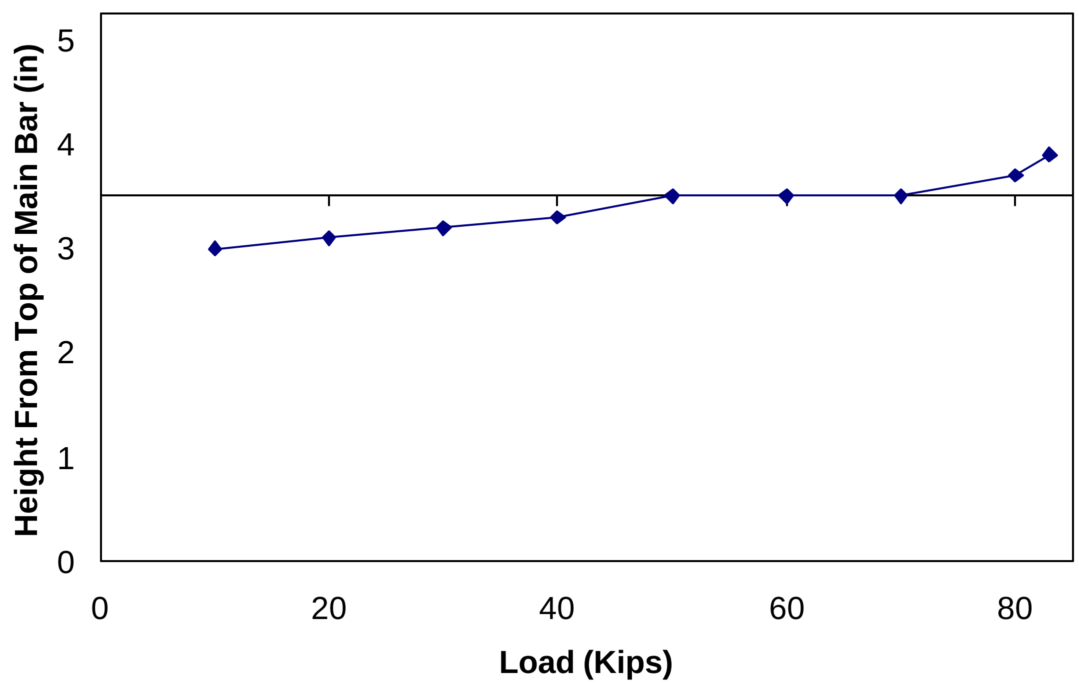

Figure B-387 Ultimate Strength Specimen #2 Main Bar #1
-Neutral Axis Location

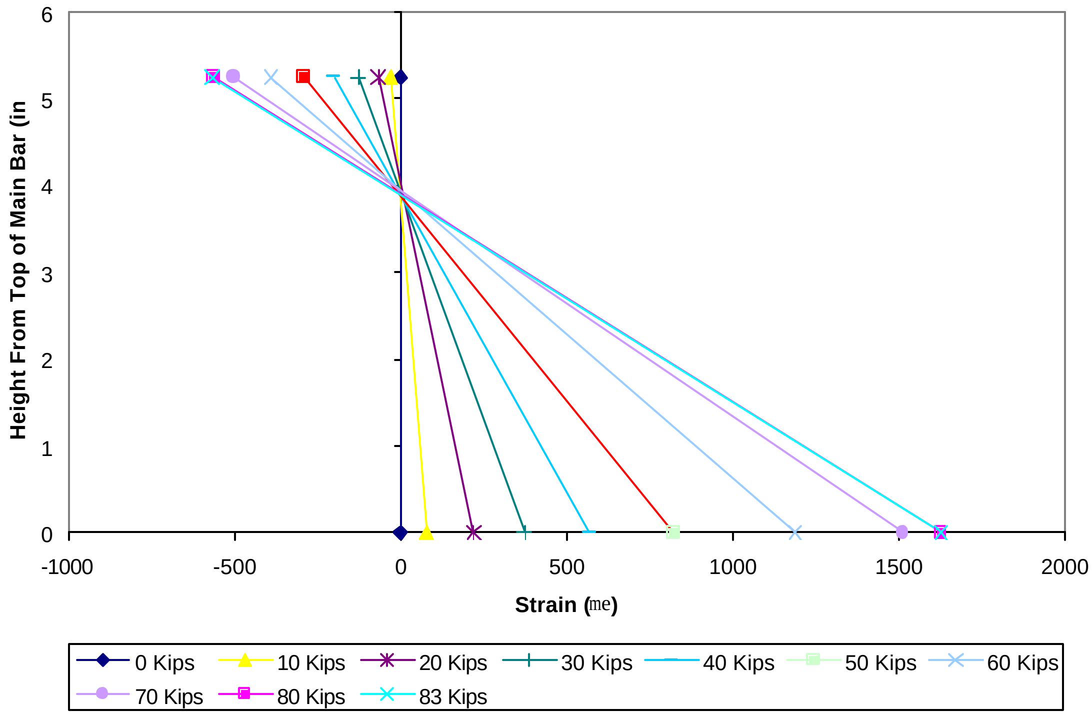

Figure B-388 Ultimate Strength Specimen #2 Main Bar #2
-Cross-Sectional Strain Distribution

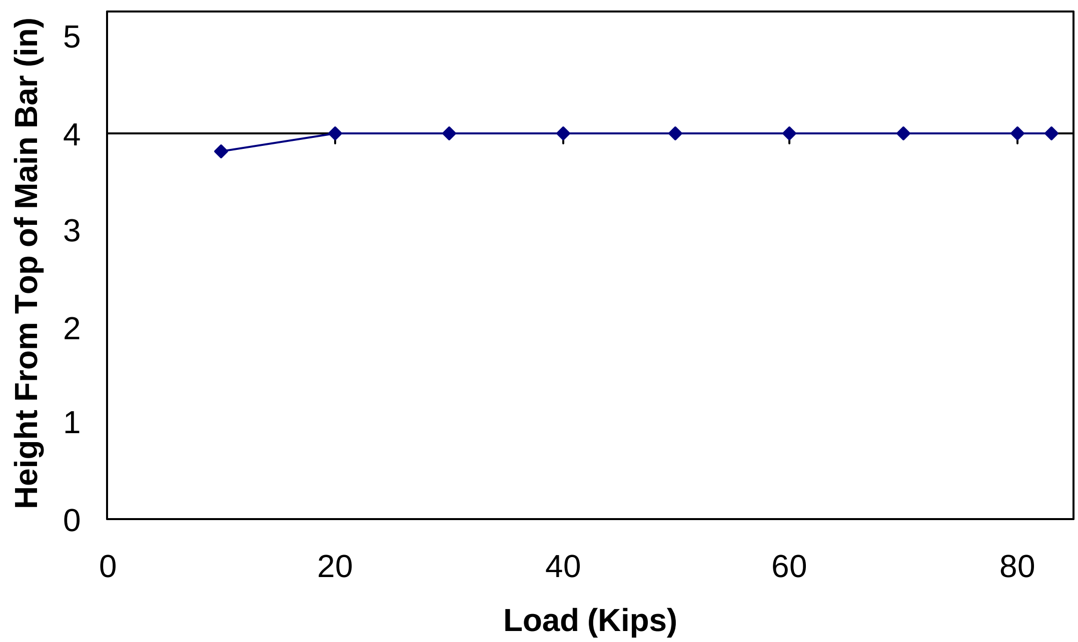

Figure B-389 Ultimate Strength Specimen #2 Main Bar #2
-Neutral Axis Location

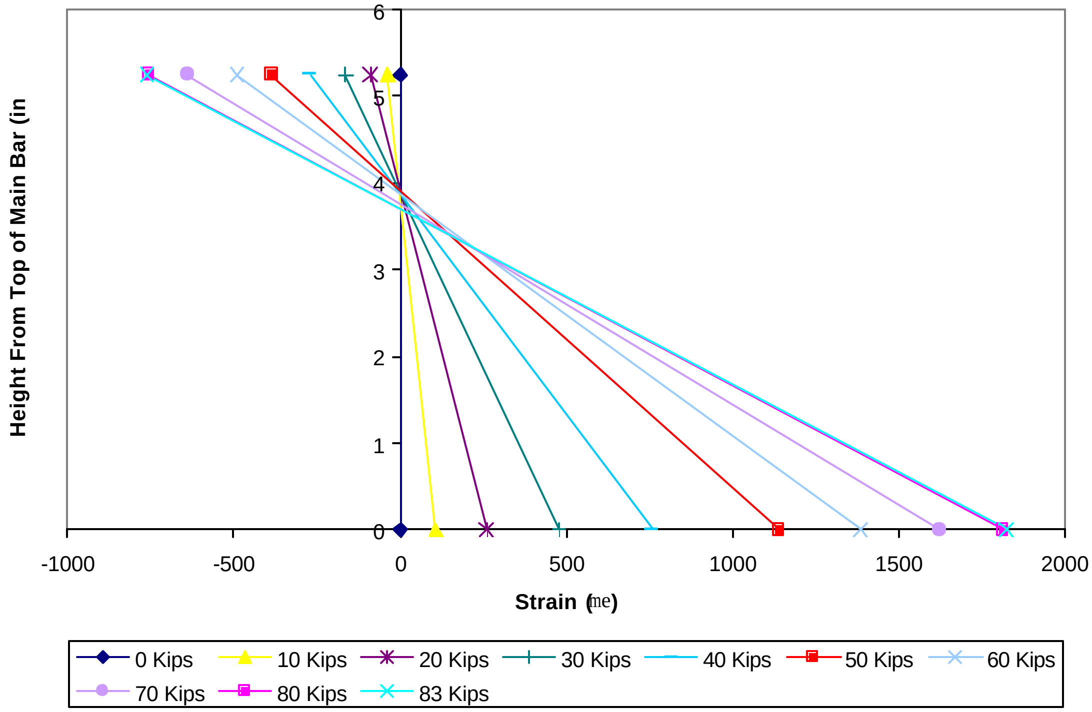

Figure B-390 Ultimate Strength Specimen #2 Main Bar #3
-Cross-Sectional Strain Distribution

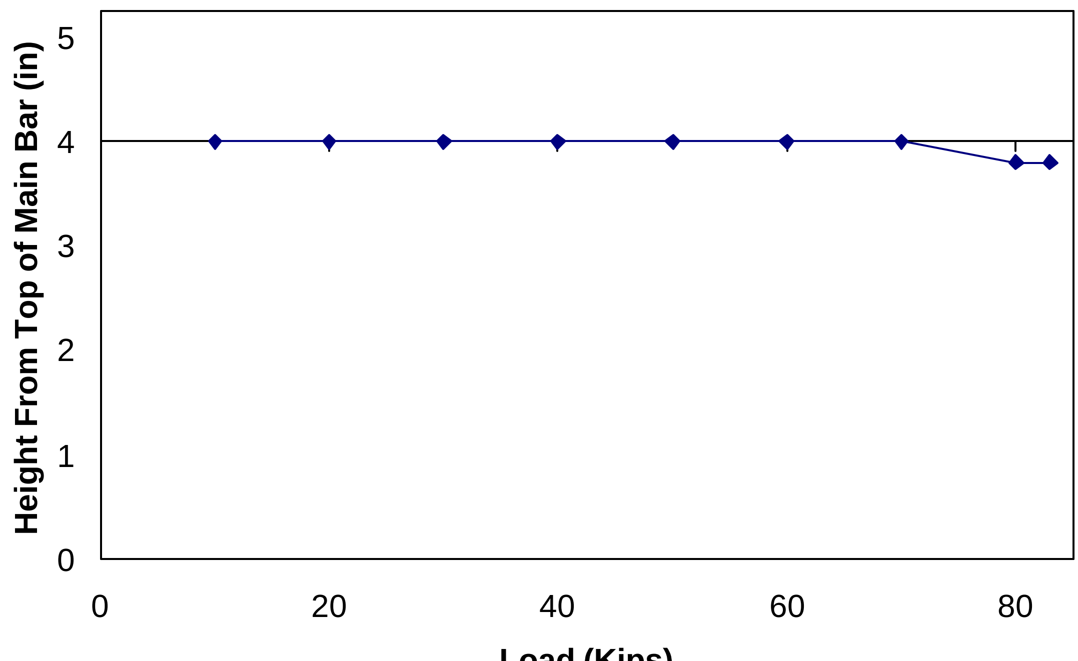

Figure B-391 Ultimate Strength Specimen #2 Main Bar #3
-Neutral Axis Location

APPENDIX C

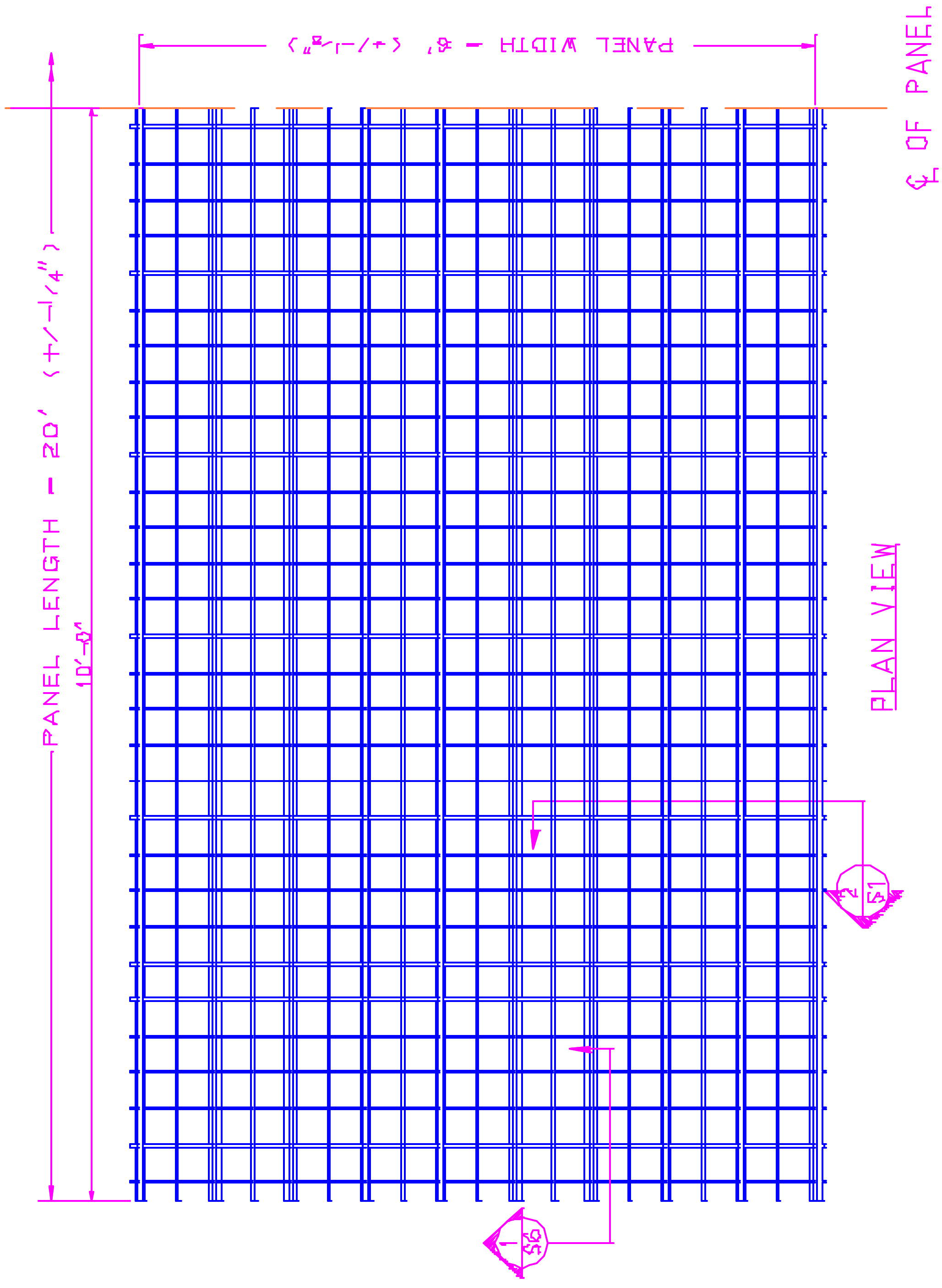

Figure C-1 Plan View of Grid Deck Specimen

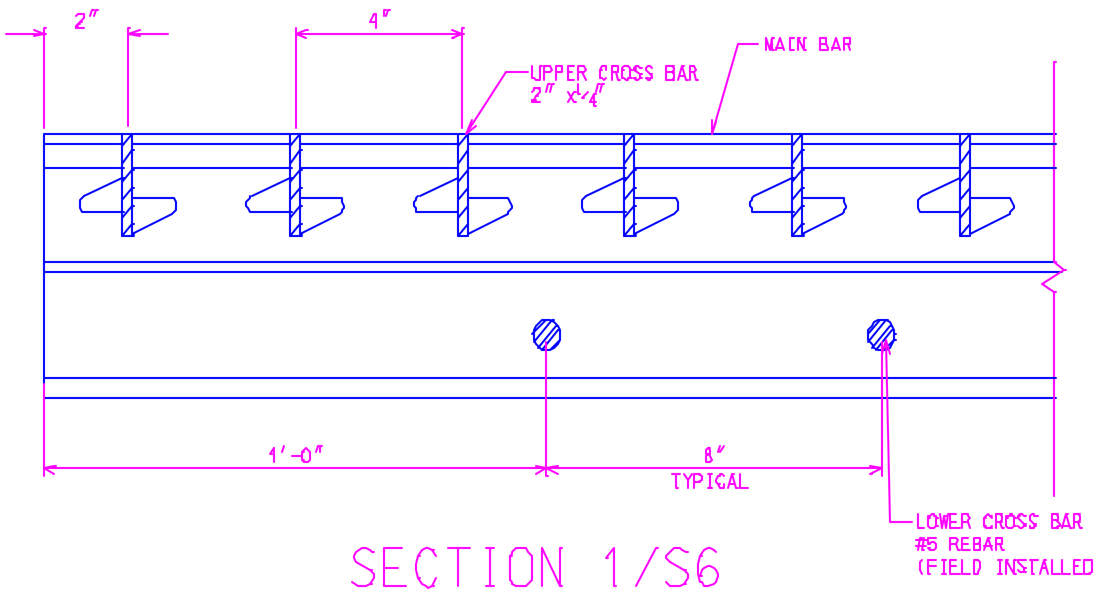

Figure C-2 Section of Grid Deck
-Typical Main Bar
-Concrete Not Shown For Clarity

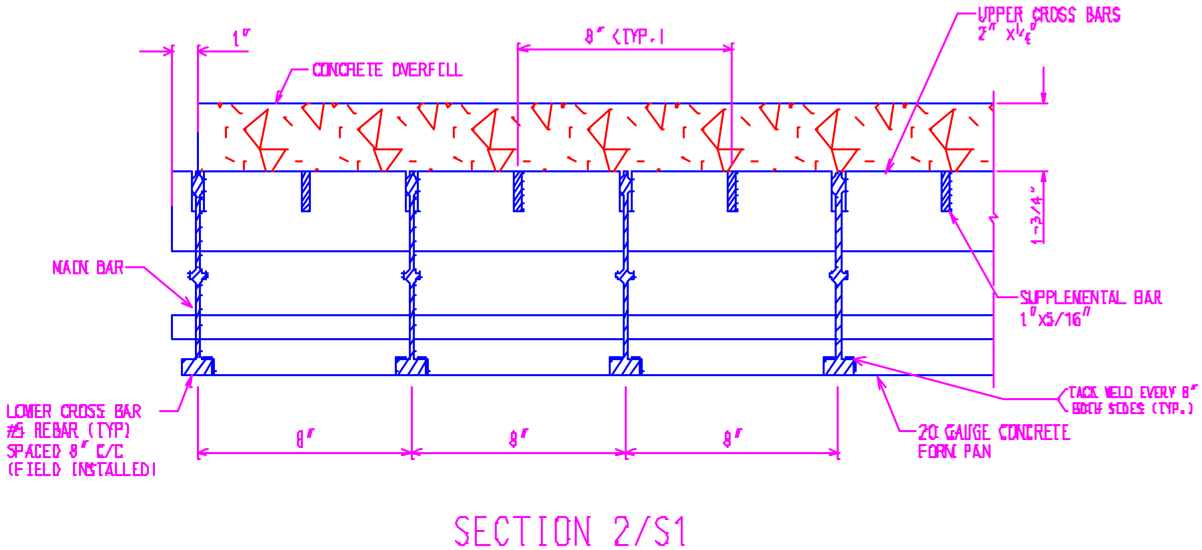

Figure C-3 Section of Grid Deck
-Concrete Not Shown For Clarity

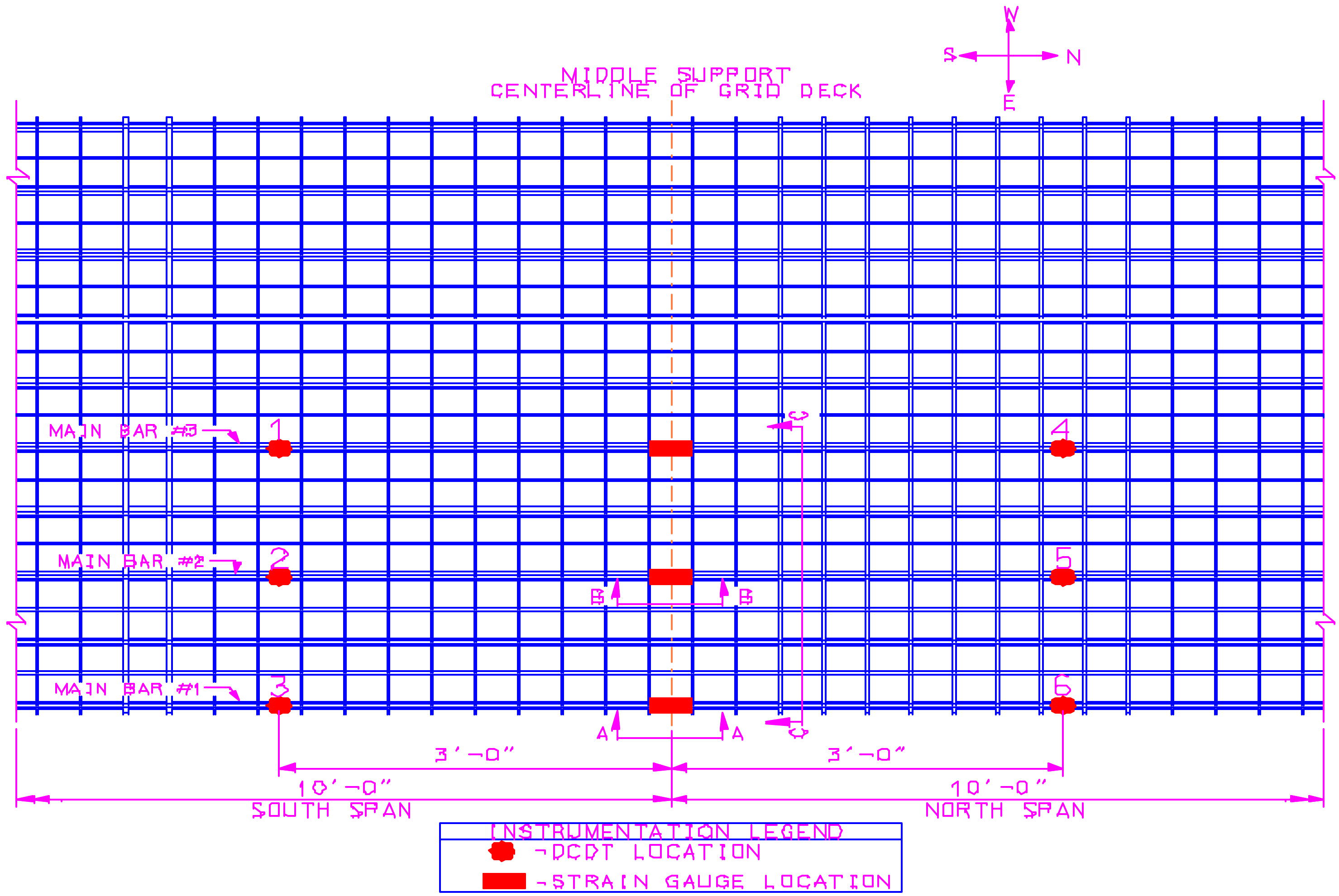

Figure C-4 Plan View of Instrumentation Layout
-Strain Gauge and DCDT Locations

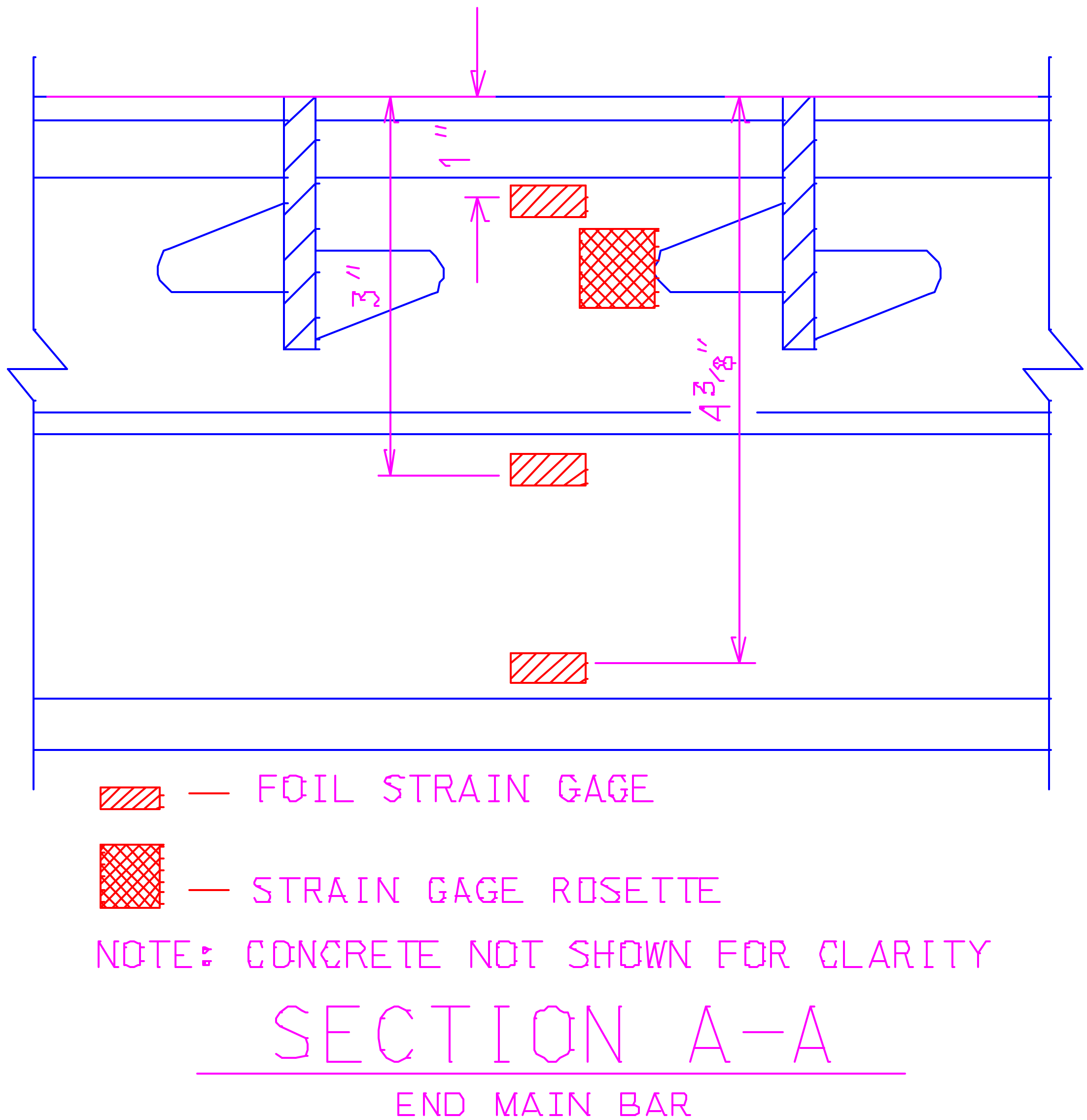

Figure C-5 Main Bar #1
-Strain Gauge Locations

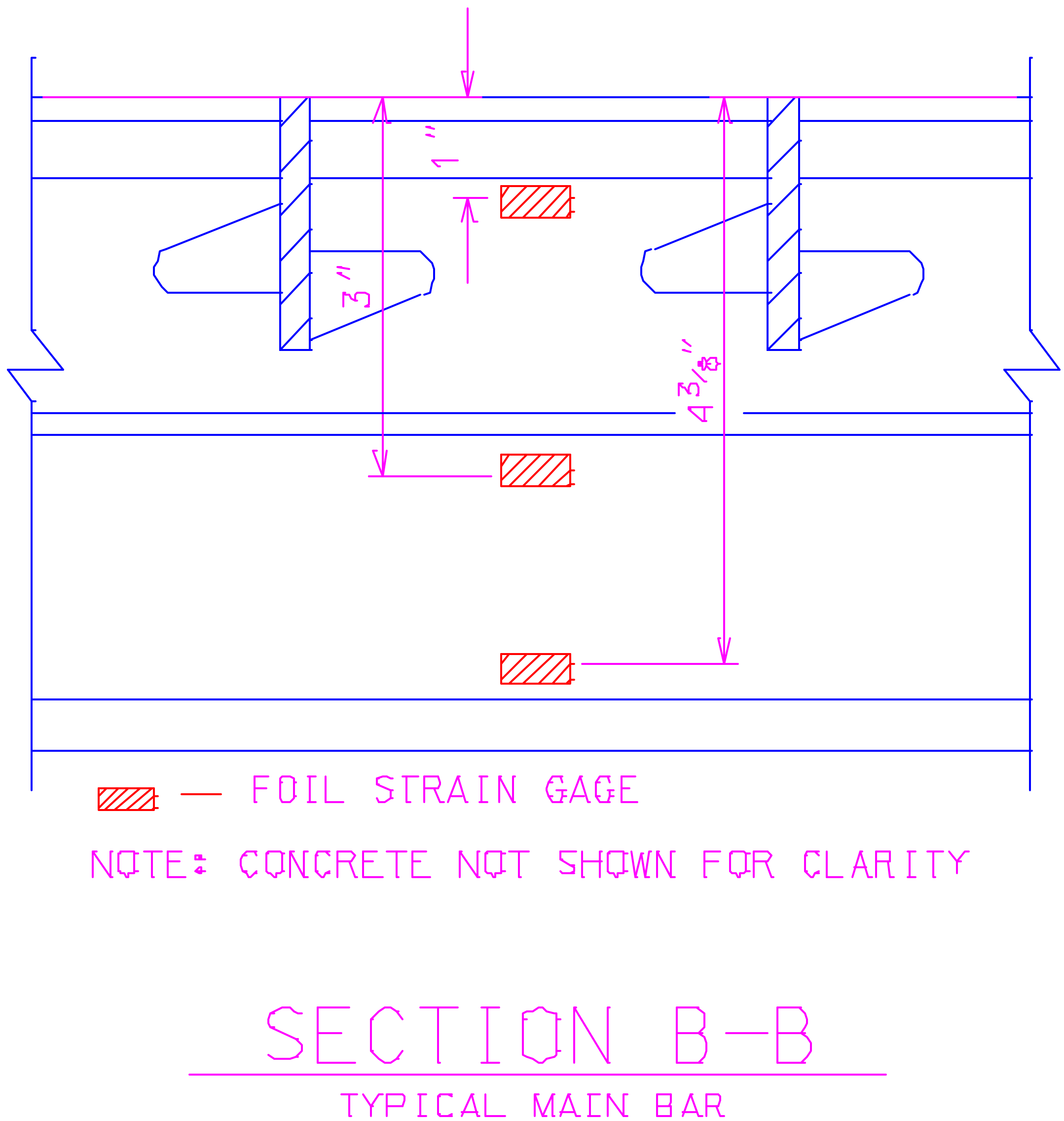

Figure C-6 Main Bar #2 & #3
-Strain Gauge Locations

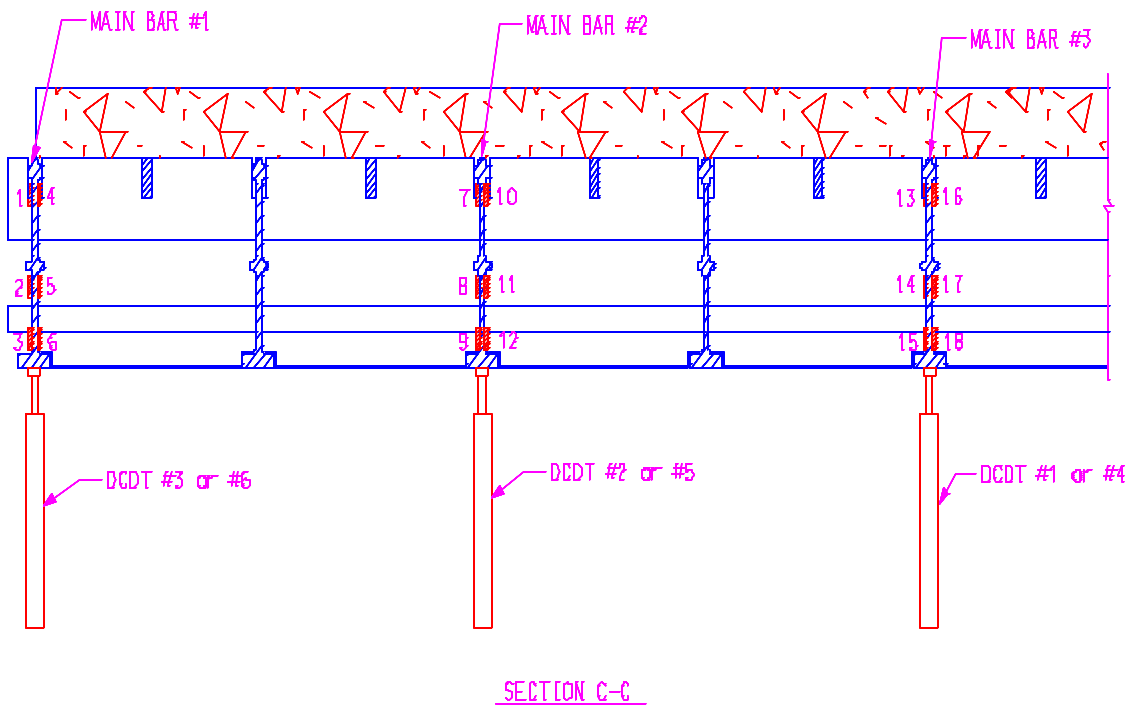

Figure C-7 Cross-Section of Instrumentation
-Foil Strain Gauge Locations
-DCDT Locations

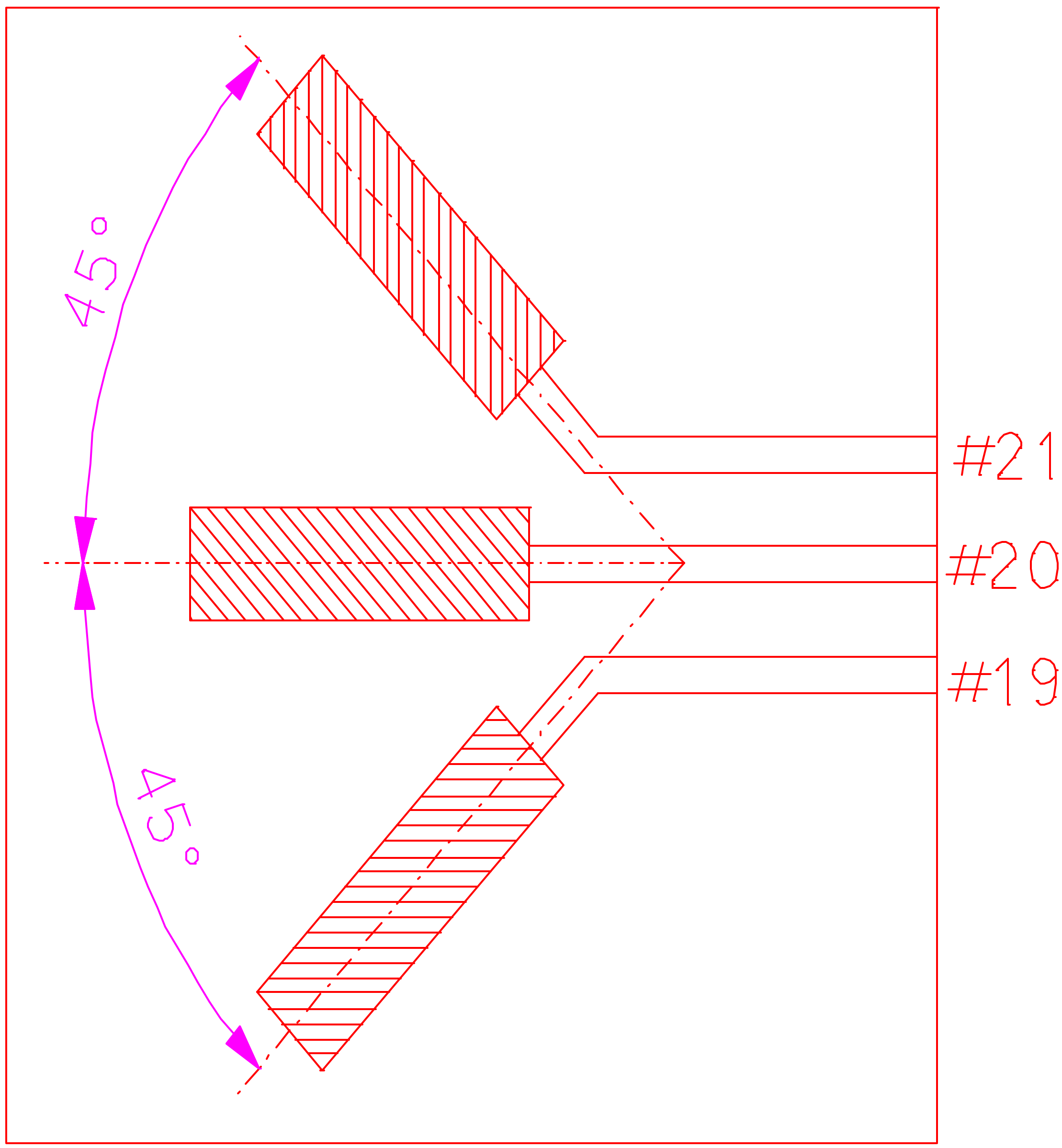

Figure C-8 Strain Gauge Rosette
-Gauge Numbers

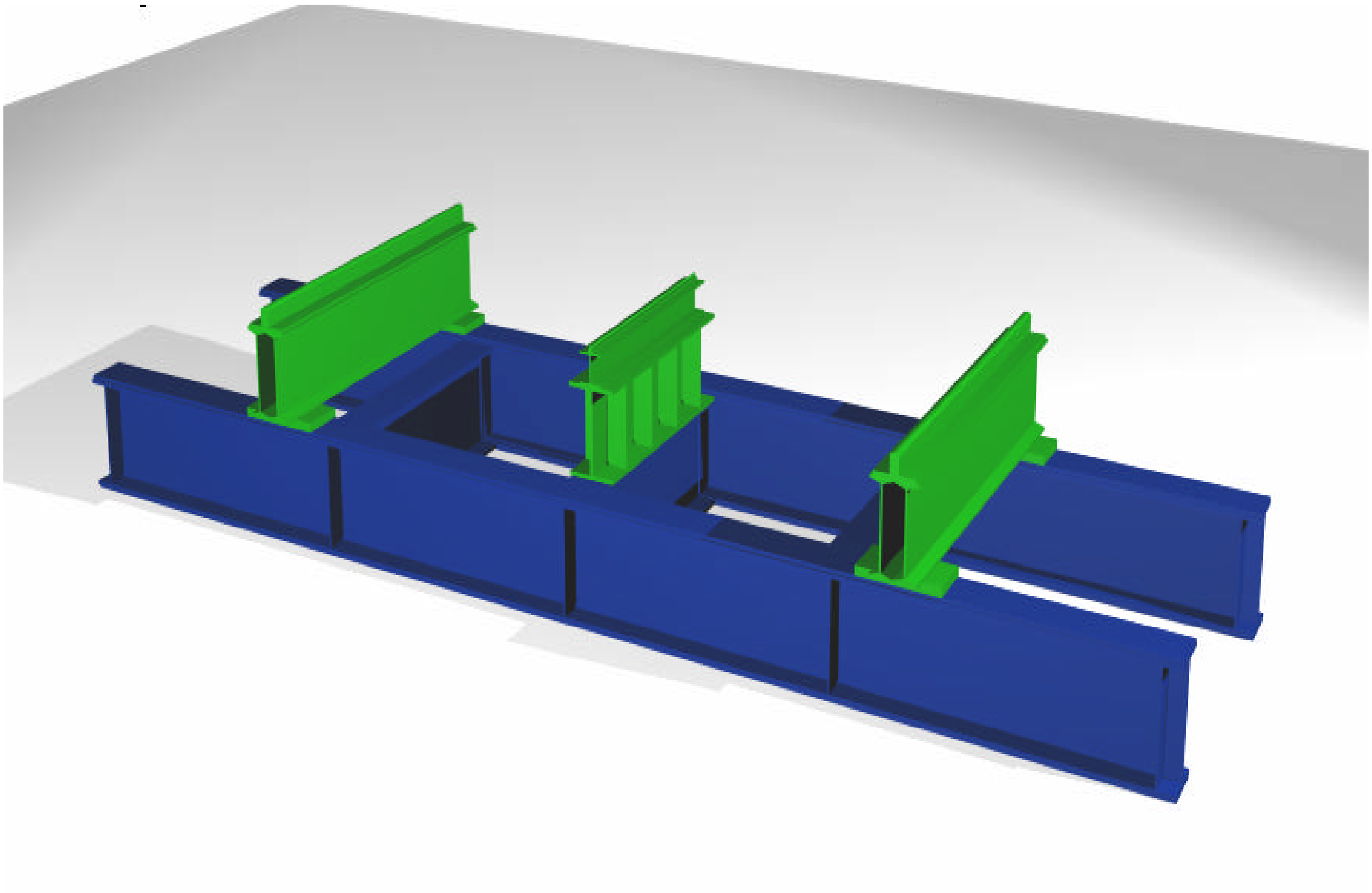

Figure C-9 View of Load Frame
-Roller Supports

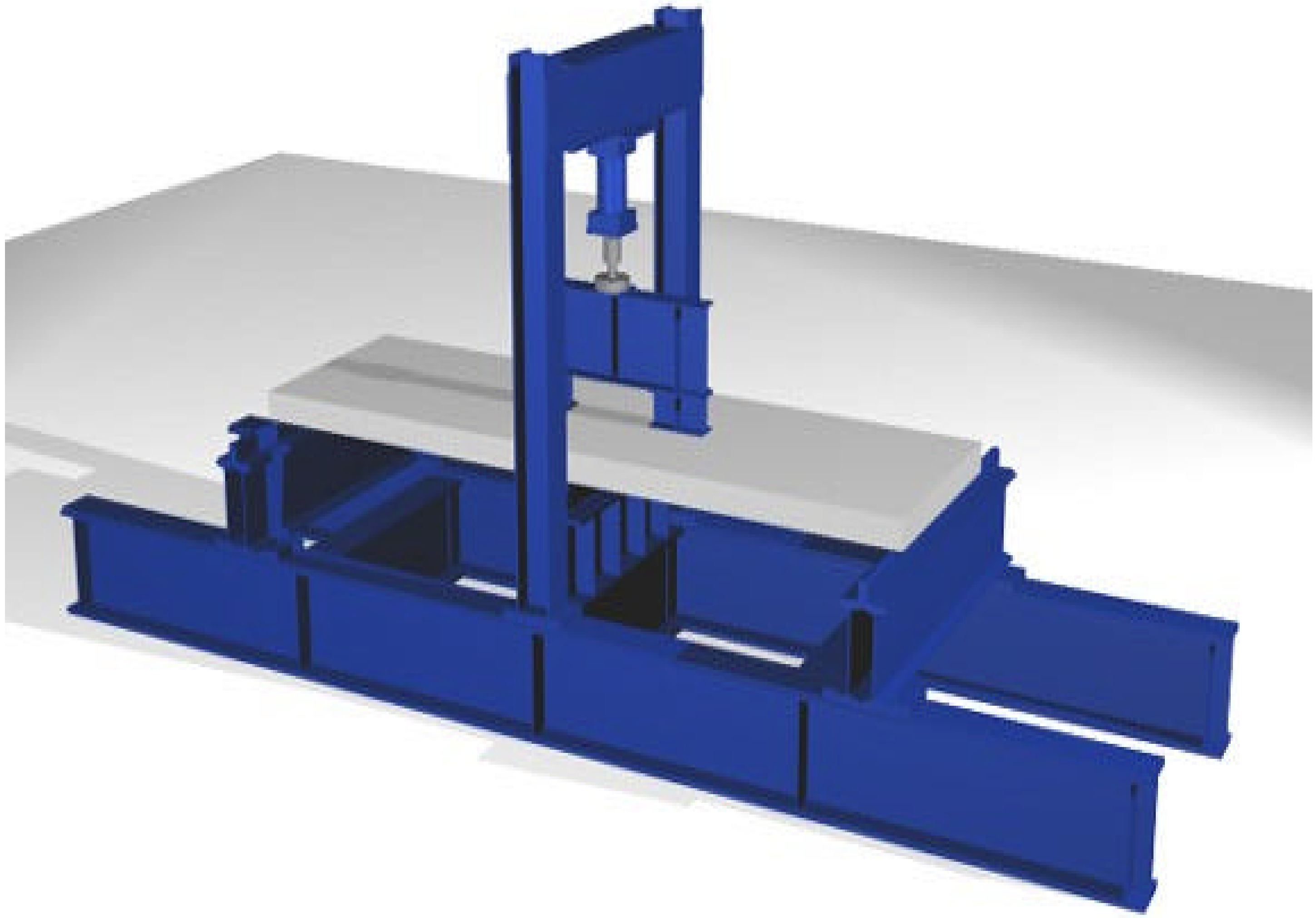

Figure C-10 Fatigue Test Set-Up

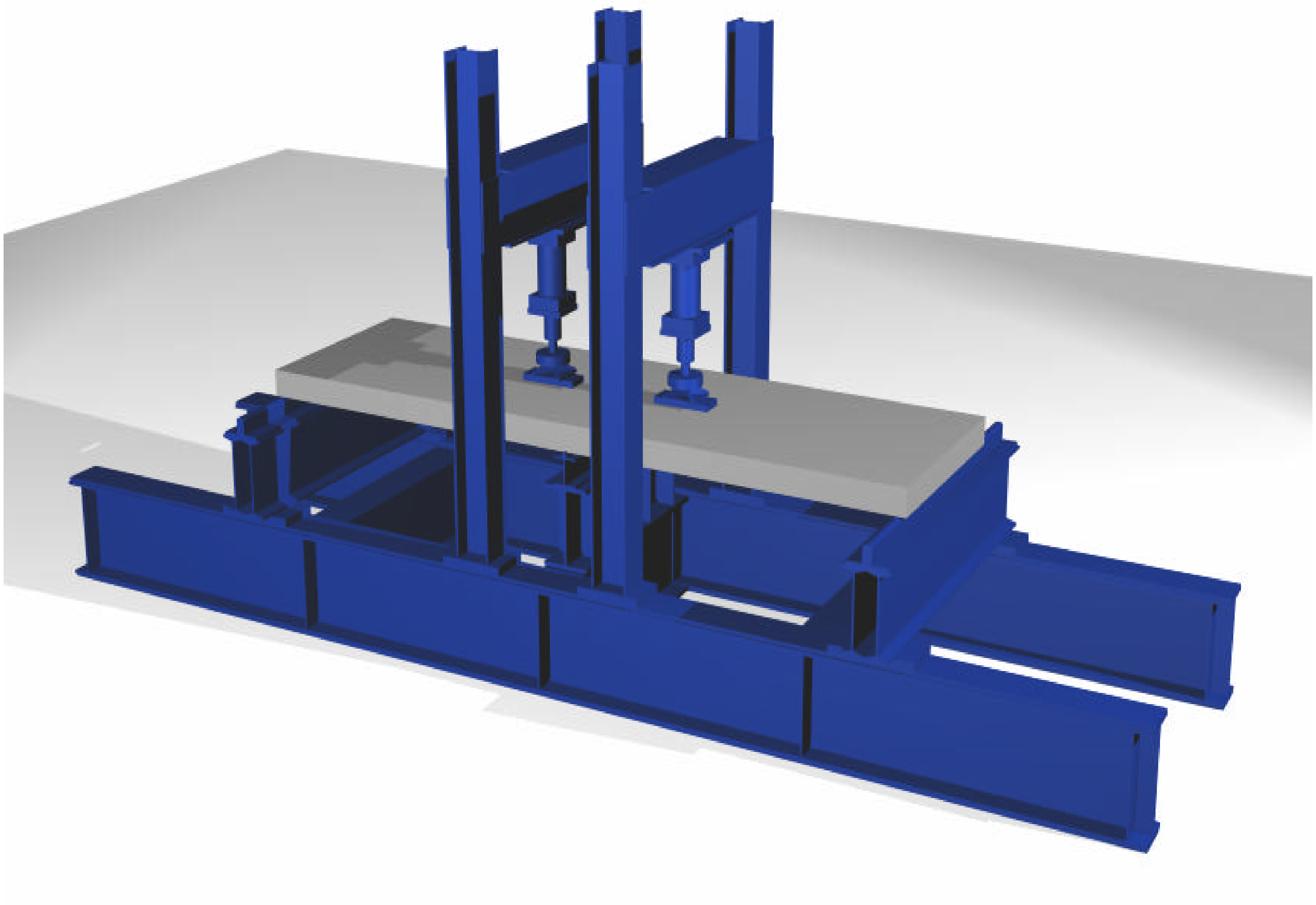

Figure C-11   Ultimate Strength Test Set-Up

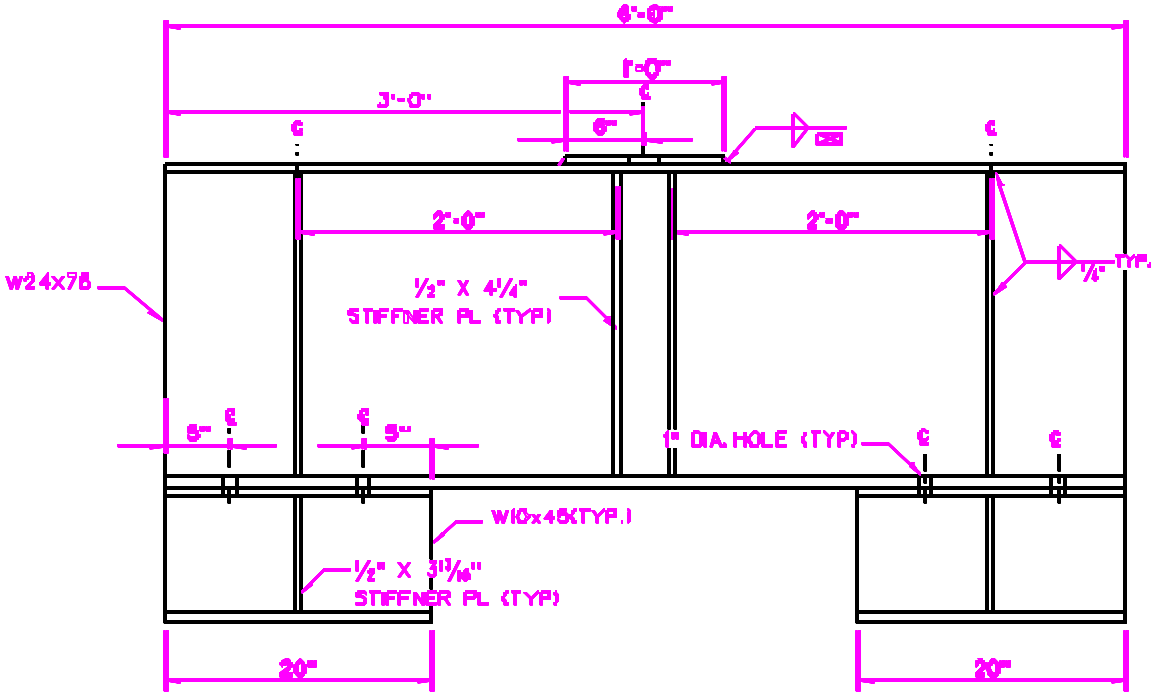

Figure C-12 Spreader Beam
-Elevation View

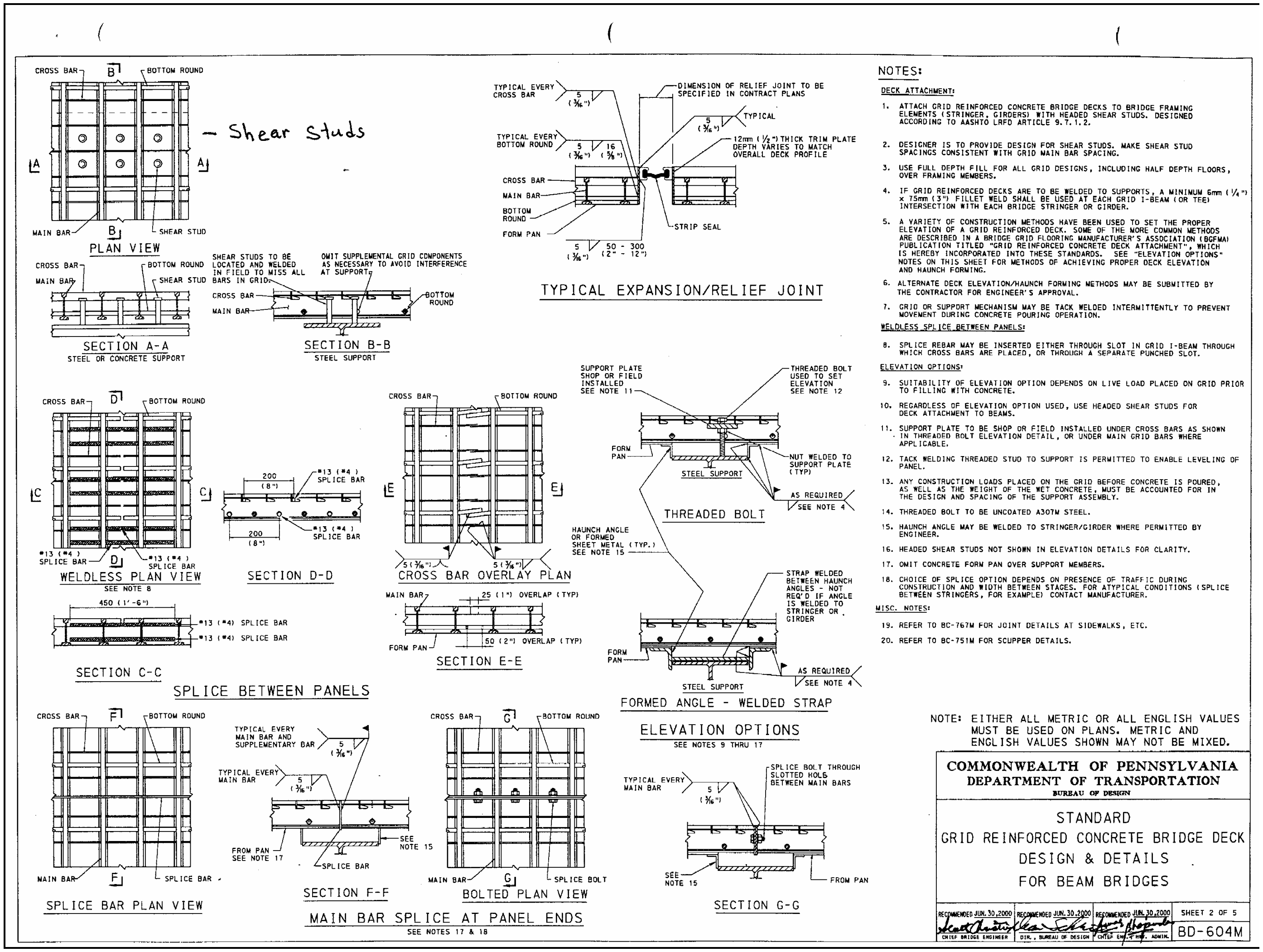

Figure C-13 Grid Deck Design Details

APPENDIX D

APPENDIX D

Table D-1
Fatigue Specimen #1 – Main Bar #3
Tabulation of Strain Gauge #13

Cycles:	Benchmark
Load (Kips)	**Strain (me)**
0	0
5	25
10	64
15	100
20	129
25	162
30	194
35	226

Cycles:	150,000
Load (Kips)	**Strain (me)**
0	0
5	9
10	27
15	49
20	75
25	101
30	127
35	155

Cycles:	300,000
Load (Kips)	**Strain (me)**
0	0
5	9
10	27
15	49
20	75
25	101
30	127
35	155

Cycles:	450,000
Load (Kips)	**Strain (me)**
0	0
5	10
10	29
15	47
20	67
25	86
30	106
35	132

Cycles:	600,000
Load (Kips)	**Strain (me)**
0	0
5	11
10	31
15	50
20	70
25	87
30	106
35	126

Cycles:	750,000
Load (Kips)	**Strain (me)**
0	0
5	13
10	31
15	49
20	69
25	88
30	108
35	135

Cycles:	900,000
Load (Kips)	**Strain (me)**
0	0
5	12
10	30
15	50
20	69
25	87
30	106
35	129

Cycles:	1,050,000
Load (Kips)	**Strain (me)**
0	0
5	14
10	33
15	58
20	83
25	110
30	133
35	156

Cycles:	1,200,000
Load (Kips)	**Strain (me)**
0	0
5	9
10	27
15	49
20	75
25	101
30	127
35	155

Cycles:	1,350,000
Load (Kips)	**Strain (me)**
0	0
5	9
10	27
15	49
20	75
25	101
30	127
35	155

Cycles:	1,500,000
Load (Kips)	**Strain (me)**
0	0
5	13
10	33
15	58
20	87
25	117
30	143
35	167

Cycles:	1,650,000
Load (Kips)	**Strain (me)**
0	0
5	19
10	47
15	74
20	102
25	128
30	149
35	174

Cycles:	1,800,000
Load (Kips)	**Strain (me)**
0	0
5	14
10	35
15	58
20	81
25	108
30	131
35	155

Cycles:	1,950,000
Load (Kips)	**Strain (me)**
0	0
5	17
10	39
15	68
20	98
25	127
30	152
35	179

Cycles:	2,100,000
Load (Kips)	**Strain (me)**
0	0
5	11
10	32
15	56
20	87
25	114
30	138
35	164

Cycles:	2,250,000
Load (Kips)	**Strain (me)**
0	0
5	13
10	40
15	67
20	97
25	124
30	150
35	175

Cycles:	2,400,000
Load (Kips)	**Strain (me)**
0	0
5	1
10	21
15	50
20	75
25	103
30	130
35	156

Cycles:	2,550,000
Load (Kips)	**Strain (me)**
0	0
5	10
10	32
15	59
20	87
25	117
30	143
35	169

Cycles:	2,700,000
Load (Kips)	**Strain (me)**
0	0
5	14
10	35
15	60
20	87
25	115
30	141
35	168

Cycles:	2,850,000
Load (Kips)	**Strain (me)**
0	0
5	15
10	36
15	62
20	91
25	123
30	151
35	175

Cycles:	3,000,000
Load (Kips)	**Strain (me)**
0	0
5	14
10	34
15	59
20	88
25	118
30	144
35	169

Cycles:	3,150,000
Load (Kips)	**Strain (me)**
0	0
5	12
10	28
15	43
20	62
25	81
30	100
35	121

Cycles:	3,300,000
Load (Kips)	**Strain (me)**
0	0
5	14
10	31
15	50
20	71
25	95
30	126
35	153

Cycles:	3,450,000
Load (Kips)	**Strain (me)**
0	0
5	11
10	28
15	45
20	68
25	99
30	130
35	159

Cycles:	3,600,000
Load (Kips)	**Strain (me)**
0	0
5	12
10	29
15	49
20	71
25	96
30	126
35	155

Cycles:	3,750,000
Load (Kips)	**Strain (me)**
0	0
5	9
10	28
15	46
20	69
25	96
30	127
35	155

Cycles:	3,900,000
Load (Kips)	**Strain (me)**
0	0
5	13
10	32
15	51
20	79
25	108
30	138
35	161

Cycles:	4,050,000
Load (Kips)	**Strain (me)**
0	0
5	14
10	32
15	51
20	71
25	99
30	130
35	160

Cycles:	4,200,000
Load (Kips)	**Strain (me)**
0	0
5	23
10	53
15	86
20	120
25	153
30	179
35	209

Cycles:	*4,350,000
Load (Kips)	**Strain (me)**
0	0
5	45
10	86
15	124
20	166
25	203
30	232
35	266

**Strain Gauge #13 quit working after 4,350,000 cycles of load.*

Table D-2
Fatigue Specimen #1-Main Bar #1
Tabulation of Strain Gauge Rosette

Cycles: Benchmark			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	10	12
10	-1	22	25
15	-1	33	37
20	-2	43	47
25	-4	54	57
30	-6	64	68
35	-6	75	76

Cycles: 150,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	4	6
10	-3	11	12
15	-4	19	21
20	-6	26	29
25	-7	34	38
30	-6	43	45
35	-7	51	52

Cycles: 300,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	4	6
10	-3	11	12
15	-4	19	21
20	-6	26	29
25	-7	34	38
30	-6	43	45
35	-7	51	52

Cycles: 450,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	4	4
10	-2	9	9
15	-3	14	14
20	-5	19	20
25	-5	25	24
30	-5	30	29
35	-5	38	36

Cycles: 600,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	4	6
10	-3	11	13
15	-4	16	18
20	-4	22	23
25	-4	27	27
30	-5	32	33
35	-5	37	38

Cycles: 750,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	4	5
10	-2	9	9
15	-3	15	16
20	-3	21	20
25	-4	26	25
30	-3	32	31
35	-4	39	37

Cycles: 900,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	4	6
10	-3	10	11
15	-4	16	17
20	-5	21	22
25	-5	27	28
30	-5	32	33
35	-5	39	38

Cycles: 1,050,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	6	8
10	-2	12	14
15	-3	19	22
20	-4	26	28
25	-4	34	34
30	-5	41	41
35	-6	47	47

Cycles: 1,200,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	4	6
10	-3	11	12
15	-4	19	21
20	-6	26	29
25	-7	34	38
30	-6	43	45
35	-7	51	52

Cycles: 1,350,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	4	6
10	-3	11	12
15	-4	19	21
20	-6	26	29
25	-7	34	38
30	-6	43	45
35	-7	51	52

Cycles: 1,500,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	5	6
10	-3	12	13
15	-5	20	21
20	-5	29	29
25	-5	38	38
30	-5	46	45
35	-5	52	50

Cycles: 1,650,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	7	10
10	-4	16	18
15	-5	24	23
20	-6	33	30
25	-7	41	33
30	-8	48	41
35	-10	55	49

Cycles: 1,800,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	4	8
10	-2	11	16
15	-3	18	22
20	-6	25	25
25	-7	30	29
30	-8	36	33
35	-10	42	38

Cycles: 1,950,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	0	8	13
10	0	17	23
15	-1	27	34
20	-1	37	41
25	0	47	51
30	0	56	60
35	0	64	68

Cycles: 2,100,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-2	3	3
10	-4	12	9
15	-5	19	15
20	-5	29	26
25	-4	37	33
30	-5	45	40
35	-6	55	50

Cycles: 2,250,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-2	5	5
10	-4	14	16
15	-7	23	26
20	-8	32	36
25	-8	39	43
30	-9	47	51
35	-10	54	60

Cycles: 2,400,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-10	-11	-21
10	-12	-4	-10
15	-14	7	1
20	-15	14	4
25	-15	23	11
30	-16	31	17
35	-7	41	29

Cycles: 2,550,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	6	5
10	-4	13	14
15	-6	23	24
20	-8	32	33
25	-18	40	41
30	-10	48	48
35	-10	56	57

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Cycles: 2,700,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	4	6
10	-4	11	13
15	-6	19	21
20	-6	27	28
25	-6	36	33
30	-7	42	40
35	-6	51	47

Cycles: 2,850,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	3	6
10	-3	10	13
15	-5	18	21
20	-5	28	29
25	-4	38	36
30	-4	46	45
35	-6	55	53

Cycles: 3,000,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	4	3
10	-2	11	10
15	-4	19	19
20	-5	28	28
25	-5	37	34
30	-5	44	41
35	-5	53	48

Cycles: 3,150,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-2	4	3
10	-4	7	9
15	-6	13	12
20	-7	16	18
25	-6	24	25
30	-7	29	29
35	-6	35	34

Cycles: 3,300,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	4	5
10	-4	10	13
15	-5	16	20
20	-6	22	26
25	-7	28	32
30	-7	37	39
35	-7	46	47

Cycles: 3,450,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	5	3
10	-2	11	8
15	-6	17	14
20	-7	24	20
25	-8	33	26
30	-8	41	34
35	-8	50	42

Cycles: 3,600,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	3	4
10	-3	9	9
15	-4	14	18
20	-4	23	25
25	-5	30	31
30	-4	38	37
35	-5	46	45

Cycles: 3,750,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	4	3
10	-4	10	8
15	-6	15	13
20	-7	23	20
25	-8	31	26
30	-7	39	33
35	-5	48	41

Cycles: 3,900,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	3	5
10	-3	10	12
15	-5	16	18
20	-7	24	25
25	-7	32	33
30	-6	40	38
35	-6	49	45

Cycles: 4,050,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-2	6	6
10	-4	11	12
15	-5	18	19
20	-6	23	23
25	-6	30	31
30	-6	39	37
35	-7	48	46

Cycles: 4,200,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-2	10	8
10	-3	20	19
15	-4	30	29
20	-5	40	38
25	-4	49	46
30	-4	57	54
35	-6	67	64

Cycles: 4,350,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-3	15	17
10	-7	29	33
15	-8	41	44
20	-8	51	54
25	-8	62	63
30	-9	72	73
35	-12	83	84

Cycles: 4,400,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-4	11	13
10	-10	25	28
15	-14	40	42
20	-15	52	51
25	-14	65	62
30	-14	80	74
35	-17	93	88

Cycles: 4,550,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-3	9	8
10	-10	26	27
15	-13	40	42
20	-13	55	54
25	-11	68	63
30	-13	84	77
35	-15	98	91

Cycles: 4,700,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-5	9	12
10	-12	28	35
15	-13	46	51
20	-13	60	62
25	-12	73	71
30	-14	88	82
35	-17	102	99

Cycles: 4,850,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-5	8	11
10	-11	24	29
15	-14	37	43
20	-14	51	53
25	-14	63	63
30	-12	74	71
35	-15	86	81

Cycles: 5,000,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	-1	10	11
10	-8	28	31
15	-10	44	46
20	-11	61	58
25	-9	76	67
30	-12	88	80
35	-14	102	94

Table D-3
Fatigue Specimen #1
Tabulation of Main Bar Stiffness

Cycles: Benchmark			
South Main Bar	**Span Stiffness (Kips/in)**	**North Main Bar**	**Span Stiffness (Kips/in)**
#1	836.20	#1	1217.50
#2	982.51	#2	934.98
#3	1190.10	#3	1076.10

Cycles: 150,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	836.20	0%	#1	1217.50	0%
#2	982.51	0%	#2	934.98	0%
#3	1190.10	0%	#3	1076.10	0%

Cycles: 300,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	2013.00	241%	#1	1734.30	142%
#2	1088.30	111%	#2	1055.70	113%
#3	----	----	#3	1170.10	109%

---- *Denotes DCDT was off-scale, therefore no value was obtained for the stiffness*

Cycles: 450,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	1114.70	133%	#1	1387.70	114%
#2	1182.10	120%	#2	1091.20	117%
#3	1464.10	123%	#3	1240.70	115%

Cycles: 600,000					
South Span			North Span		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	1116.70	134%	#1	981.29	81%
#2	1203.90	123%	#2	1104.70	118%
#3	1517.20	127%	#3	1282.40	119%

Cycles: 750,000					
South Span			North Span		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	1043.00	125%	#1	1383.60	114%
#2	1202.50	122%	#2	1081.20	116%
#3	1461.40	123%	#3	1214.70	113%

Cycles: 900,000					
South Span			North Span		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	1098.40	131%	#1	1657.90	136%
#2	1307.40	133%	#2	1079.60	115%
#3	1578.80	133%	#3	1177.20	109%

Cycles: 1,050,000					
South Span			North Span		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	863.21	103%	#1	1064.30	87%
#2	969.39	99%	#2	906.32	97%
#3	1148.60	97%	#3	1030.70	96%

Cycles: 1,200,000					
South Span			North Span		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	870.89	104%	#1	1246.10	102%
#2	978.62	100%	#2	983.82	105%
#3	1202.50	101%	#3	1039.60	97%

Cycles: 1,350,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	870.89	104%	#1	1246.10	102%
#2	978.62	100%	#2	913.88	98%
#3	1202.50	101%	#3	1039.60	97%

Cycles: 1,500,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	820.30	98%	#1	1022.70	84%
#2	916.19	93%	#2	799.05	85%
#3	1106.40	93%	#3	871.10	81%

Cycles: 1,650,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	747.25	89%	#1	910.60	75%
#2	833.50	85%	#2	722.71	77%
#3	958.96	81%	#3	829.40	77%

Cycles: 1,800,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	821.56	98%	#1	1202.50	99%
#2	951.76	97%	#2	922.72	99%
#3	1141.50	96%	#3	1049.50	98%

Cycles: 1,950,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	755.10	90%	#1	1027.50	84%
#2	874.13	89%	#2	788.91	84%
#3	1082.80	91%	#3	896.55	83%

Cycles: 2,100,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	765.61	92%	#1	1232.00	101%
#2	866.07	88%	#2	783.06	84%
#3	1000.03	84%	#3	888.66	83%

Cycles: 2,250,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	739.06	88%	#1	1044.40	86%
#2	812.26	83%	#2	835.16	89%
#3	939.79	79%	#3	960.68	89%

Cycles: 2,400,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	771.93	92%	#1	1011.20	83%
#2	844.91	86%	#2	861.70	92%
#3	971.40	82%	#3	968.35	90%

Cycles: 2,550,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	751.30	90%	#1	1011.20	83%
#2	837.51	85%	#2	861.70	92%
#3	971.40	82%	#3	968.35	90%

Cycles: 2,700,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	781.69	93%	#1	1134.70	93%
#2	838.87	85%	#2	891.72	95%
#3	966.62	81%	#3	979.96	91%

Cycles: 2,850,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	734.82	88%	#1	496.36	41%
#2	856.42	87%	#2	806.87	86%
#3	1052.20	88%	#3	917.19	85%

Cycles: 3,000,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	761.99	91%	#1	----	----
#2	893.92	91%	#2	851.33	91%
#3	1022.71	86%	#3	973.66	90%

---- *Denotes DCDT was off-scale, therefore no value was obtained for the stiffness*

Cycles: 3,150,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	1024.00	122%	#1	1622.10	133%
#2	1195.80	122%	#2	1178.10	126%
#3	1457.20	122%	#3	1304.08	121%

Cycles: 3,300,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	848.49	101%	#1	1303.90	107%
#2	972.11	99%	#2	993.49	106%
#3	1222.70	103%	#3	1119.70	104%

Cycles: 3,450,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	762.47	91%	#1	1058.90	87%
#2	874.23	89%	#2	957.33	102%
#3	1114.70	94%	#3	1096.00	102%

Cycles: 3,600,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	841.99	101%	#1	1513.50	124%
#2	972.03	99%	#2	----	----
#3	1211.00	102%	#3	1248.90	102%

---- *Denotes DCDT was off-scale, therefore no value was obtained for the stiffness*

Cycles: 3,750,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	810.94	97%	#1	1365.80	112%
#2	956.13	97%	#2	936.16	100%
#3	----	----	#3	1072.80	100%

---- *Denotes DCDT was off-scale, therefore no value was obtained for the stiffness*

Cycles: 3,900,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	750.04	90%	#1	1401.20	115%
#2	900.63	92%	#2	941.96	101%
#3	1169.80	98%	#3	1102.80	102%

Cycles: 4,050,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	787.36	94%	#1	1234.70	101%
#2	949.24	97%	#2	948.21	101%
#3	1167.80	98%	#3	1113.70	103%

Cycles: 4,200,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	583.20	70%	#1	1026.20	84%
#2	----	----	#2	726.01	78%
#3	----	----	#3	833.66	77%

---- *Denotes DCDT was off-scale, therefore no value was obtained for the stiffness*

Cycles: 4,350,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	----	----	#1	762.49	63%
#2	567.24	58%	#2	557.49	60%
#3	----	----	#3	648.43	60%

---- *Denotes DCDT was off-scale, therefore no value was obtained for the stiffness*

Cycles: 4,400,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	----	----	#1	665.05	55%
#2	462.82	47%	#2	487.95	52%
#3	----	----	#3	565.25	53%

---- *Denotes DCDT was off-scale, therefore no value was obtained for the stiffness*

Cycles: 4,550,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	645.06	77%	#1	633.70	52%
#2	456.14	46%	#2	456.36	49%
#3	----	----	#3	651.43	61%

---- *Denotes DCDT was off-scale, therefore no value was obtained for the stiffness*

Cycles: 4,700,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	----	----	#1	576.15	47%
#2	483.32	49%	#2	426.29	46%
#3	558.19	47%	#3	490.02	46%

---- *Denotes DCDT was off-scale, therefore no value was obtained for the stiffness*

Cycles: 4,850,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	383.53	46%	#1	712.41	59%
#2	474.70	48%	#2	509.43	54%
#3	595.79	50%	#3	593.97	55%

Cycles: 5,000,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	355.41	43%	#1	629.05	52%
#2	421.61	43%	#2	488.96	52%
#3	527.30	44%	#3	528.23	49%

Table D-4
Fatigue Specimen #2-Main Bar #1
Tabulation of Strain Gauge Rosette

Cycles: Benchmark			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	5	18	17
10	13	46	47
15	25	76	77
20	42	108	105
25	51	132	132
30	56	152	160
35	61	171	181
40	67	187	202
45	72	203	222
50	76	217	237

Cycles: 150,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	4	11	13
10	9	24	27
15	14	38	42
20	19	51	57
25	24	64	72
30	31	81	90
35	35	96	109
40	39	111	128
45	42	125	144
50	45	138	157

Cycles: 300,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	4	13	13
10	9	26	28
15	13	37	42
20	18	50	56
25	23	62	71
30	27	77	87
35	33	93	106
40	37	108	124
45	40	121	139
50	43	134	152

Cycles: 450,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	3	9	12
10	8	22	26
15	11	32	39
20	17	45	53
25	21	58	66
30	26	68	81
35	30	83	97
40	35	98	114
45	39	111	130
50	41	123	142

Cycles: 600,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	3	10	12
10	7	22	25
15	11	33	38
20	14	45	52
25	18	55	65
30	21	67	77
35	25	78	92
40	29	94	109
45	32	105	123
50	35	115	135

Cycles: 750,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	3	11	13
10	7	22	26
15	12	34	40
20	16	46	55
25	20	57	68
30	25	70	82
35	29	82	98
40	31	95	113
45	34	106	126
50	36	117	139

Cycles: 900,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	2	10	11
10	7	22	25
15	11	35	40
20	14	46	53
25	17	57	65
30	21	68	79
35	24	80	93
40	27	92	109
45	30	104	123
50	32	115	136

Cycles: 1,050,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	2	10	10
10	5	20	24
15	9	32	37
20	18	48	54
25	20	58	65
30	21	65	76
35	23	74	87
40	27	86	102
45	29	97	115
50	30	106	125

Cycles: 1,200,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	6	13	14
10	10	24	27
15	12	35	40
20	16	46	52
25	19	56	65
30	23	66	77
35	25	75	89
40	29	86	100
45	30	96	113
50	33	106	124

Cycles: 1,350,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	1	9	10
10	4	19	24
15	8	30	37
20	12	42	50
25	15	51	61
30	18	61	73
35	19	70	83
40	23	80	96
45	25	88	106
50	27	98	116

Cycles: 1,500,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	4	13	12
10	10	24	25
15	15	38	41
20	19	48	53
25	23	58	66
30	24	66	77
35	29	78	88
40	32	87	99
45	31	94	109
50	35	104	119

Cycles: 1,700,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	6	13	14
10	12	26	27
15	17	38	41
20	22	50	54
25	27	61	68
30	29	71	78
35	33	80	89
40	34	89	99
45	37	98	109
50	40	106	119

Cycles: 1,850,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	3	9	12
10	6	19	24
15	9	31	36
20	12	40	48
25	15	50	59
30	18	58	70
35	19	67	81
40	22	76	91
45	23	84	101
50	25	92	109

Cycles: 2,000,000			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
5	10	14	15
10	12	23	27
15	20	39	42
20	22	48	54
25	25	57	66
30	27	65	77
35	34	79	91
40	36	87	101
45	38	96	111
50	42	105	121

Table D-5
Fatigue Specimen #2
Tabulation of Main Bar Stiffness

Cycles: Benchmark			
South Main Bar	**Span Stiffness (Kips/in)**	**North Main Bar**	**Span Stiffness (Kips/in)**
#1	617.92	#1	717.35
#2	720.02	#2	879.28
#3	906.14	#3	993.50

Cycles: 150,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	617.92	0%	#1	717.35	0%
#2	720.02	0%	#2	879.28	0%
#3	906.14	0%	#3	993.50	0%

Cycles: 300,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	625.89	101%	#1	733.69	102%
#2	742.00	103%	#2	886.61	101%
#3	905.99	100%	#3	1170.10	118%

Cycles: 450,000					
South Span			**North Span**		
Main Bar	**Stiffness (Kips/in)**	**% of Benchmark**	**Main Bar**	**Stiffness (Kips/in)**	**% of Benchmark**
#1	654.44	106%	#1	789.12	110%
#2	782.65	109%	#2	961.00	109%
#3	1003.50	111%	#3	1115.30	112%

Cycles: 600,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	667.81	108%	#1	778.71	109%
#2	786.41	109%	#2	950.05	108%
#3	993.74	110%	#3	1129.70	114%

Cycles: 750,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	650.75	105%	#1	796.65	111%
#2	797.12	111%	#2	957.22	109%
#3	1009.60	111%	#3	1158.00	117%

Cycles: 900,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	657.24	106%	#1	795.92	111%
#2	809.01	112%	#2	980.06	111%
#3	995.87	110%	#3	1074.90	108%

Cycles: 1,050,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	679.56	110%	#1	801.91	112%
#2	801.91	111%	#2	983.41	112%
#3	968.99	107%	#3	1164.10	117%

Cycles: 1,200,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	691.60	112%	#1	834.06	116%
#2	824.67	115%	#2	990.02	113%
#3	1017.20	112%	#3	1202.00	121%

Cycles: 1,350,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	694.25	112%	#1	841.43	117%
#2	823.45	114%	#2	998.45	114%
#3	1018.80	112%	#3	1219.60	123%

Cycles: 1,500,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	711.47	115%	#1	854.40	119%
#2	853.54	119%	#2	999.17	114%
#3	1102.30	122%	#3	1260.70	127%

Cycles: 1,700,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	702.54	114%	#1	861.86	120%
#2	849.92	118%	#2	995.67	113%
#3	1086.40	120%	#3	1264.50	127%

Cycles: 1,850,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	693.40	112%	#1	859.79	120%
#2	862.19	120%	#2	1012.20	115%
#3	1272.70	140%	#3	1289.10	130%

Cycles: 2,000,000					
South Span			North Span		
Main Bar	Stiffness (Kips/in)	% of Benchmark	Main Bar	Stiffness (Kips/in)	% of Benchmark
#1	702.36	114%	#1	863.02	120%
#2	849.92	118%	#2	970.87	110%
#3	1033.20	114%	#3	1242.40	125%

Table D-6
Ultimate Strength Tests
Tabulation of Peak Load Values

Ultimate Strength Tests		
Test #	**Ultimate Load (Kips)**	**Failure Mode**
1	126.00	Sudden Debonding of Concrete
2	83.00	Plastic Collapse Mechanism (South Span)
3	73.00	Plastic Collapse Mechanism (South Span)
4	70.10	Plastic Collapse Mechanism (South Span)

Table D-7
Ultimate Strength Specimen #1-Main Bar #1
Tabulation of Strain Gauge Rosette

Cycles: Benchmark			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
10	8	50	48
20	14	124	116
30	29	204	197
40	47	285	268
50	63	365	336
60	84	445	393
70	86	451	396
80	108	537	460
90	128	631	522
100	161	740	587
110	202	865	660
120	212	1027	758
126	238	1121	798

Table D-8
Ultimate Strength Specimen #2-Main Bar #1
Tabulation of Strain Gauge Rosette

Cycles: Benchmark			
Load (Kips)	**Strain Gauge #19 (me)**	**Strain Gauge #20 (me)**	**Strain Gauge #21 (me)**
0	0	0	0
10	0	0	75
20	0	0	132
30	0	0	178
40	0	0	218
50	0	0	260
60	0	0	312
70	0	0	436
80	0	0	522
83	0	0	522

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